DOCUMENT RESUME

ED 220 599 CE 033 393

AUTHOR Richards, Whitman, Ed.; Dismukes, Key, Ed.
TITLE Vision Research for Flight Simulation. Final Report.
INSTITUTION National Academy of Sciences - National Research Council, Washington, D.C. Assembly of Behavioral and Social Sciences.
SPONS AGENCY Air Force Human Resources Lab., Williams AFB, Ariz.
REPORT NO AFHRL-TR-82-6
PUB DATE Jul 82
CONTRACT F33615-80-C-0009
NOTE 109p.

EDRS PRICE MF01/PC05 Plus Postage.
DESCRIPTORS Adult Education; Cooperation; *Flight Training; Military Training; *Research Methodology; *Research Needs; *Simulation; *Vision; Workshops
IDENTIFIERS *Flight Simulation; *Visual Displays

ABSTRACT

Based on a workshop on vision research issues in flight-training simulators held in June 1980, this report focuses on approaches for the conduct of research on what visual information is needed for simulation and how it can best be presented. An introduction gives an overview of the workshop and describes the contents of the report. Section 1 discusses the general need for research in the area and suggests ways to facilitate the research needed and to stimulate interaction between scientists and simulation researchers. Section 2 describes some technical problems in more detail and gives a few examples of applying research strategies to these problems. Five appendix papers provide examples of research strategies. Primary emphasis is given to low-level flight, in which extraction of visual information from terrain features is crucial but little understood. Values and pitfalls are described of these strategies for exploring which visual features should be used in low-level flight: systematic condensation of opinions, particularly of pilots (appendix A); geometric analysis of terrain information potentially usable (B); and psychophysical analysis of visual processing modalities (C and D). Appendix E examines equipment requirements for display of visual information. Appendix F lists workshop topics and participants. (YLB)

****
* Reproductions supplied by EDRS are the best that can be made *
* from the original document. *
****

CE

AFHRL-TR-82-6

AIR FORCE

HUMAN RESOURCES

VISION RESEARCH FOR FLIGHT SIMULATION

Edited by

Whitman Richards
Key Dismukes

National Research Council
Assembly of Behavioral and Social Sciences
2101 Constitution Avenue
Washington, D.C. 20418

OPERATIONS TRAINING DIVISION
Williams Air Force Base, Arizona 85224

July 1982

Final Report

Approved for public release; distribution unlimited.

LABORATORY

ED220599

CG 033,393

U.S. DEPARTMENT OF EDUCATION
NATIONAL INSTITUTE OF EDUCATION
EDUCATIONAL RESOURCES INFORMATION
CENTER (ERIC)
✓ This document has been reproduced as received from the person or organization originating it.
☐ Minor changes have been made to improve reproduction quality.
- Points of view or opinions stated in this document do not necessarily represent official NIE position or policy.

AIR FORCE SYSTEMS COMMAND
BROOKS AIR FORCE BASE, TEXAS 78235

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely Government-related procurement, the United States Government incurs no responsibility or any obligation whatsoever. The fact that the Government may have formulated or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication, or otherwise in any manner construed, as licensing the holder, or any other person or corporation; or as conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

The Public Affairs Office has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

THOMAS M. LONGRIDGE
Contract Monitor

MILTON E. WOOD, Technical Director
Operations Training Division

RONALD W. TERRY, Colonel, USAF
Commander

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
AFHRL-TR-82-6

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
VISION RESEARCH FOR FLIGHT SIMULATION

5. TYPE OF REPORT & PERIOD COVERED
Final

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
Whitman Richards
Key Dismukes

8. CONTRACT OR GRANT NUMBER(s)
F33615-80-C-0009

9. PERFORMING ORGANIZATION NAME AND ADDRESS
National Research Council
Assembly of Behavioral and Social Sciences
2101 Constitution Avenue
Washington, D.C. 20418

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
61101F
ILIR0047

11. CONTROLLING OFFICE NAME AND ADDRESS
HQ Air Force Human Resources Laboratory (AFSC)
Brooks Air Force Base, Texas 78235

12. REPORT DATE
July 1982

13. NUMBER OF PAGES
108

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
Operations Training Division
Air Force Human Resources Laboratory
Williams Air Force Base, Arizona 85224

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)
Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

flight simulation	visual cues
low-level flight	visual displays
vision	visual information processing

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report is based on a workshop organized by the Committee on Vision of the National Research Council and by the Operations Training Division of the Air Force Human Resources Laboratory at Williams AFB in June 1980. The workshop brought together vision scientists from academia and government scientists concerned with research on visual displays for flight simulation. The principal objective was to provide recommendations concerning fruitful approaches for the conduct of research on what visual information is needed for simulation and how it might best be presented. Low-level flight was used as a focus for discussion of problem-solving approaches. The technical report prepared by the steering group provides examples of particular research strategies that might help elucidate several of the long-range issues in visual simulation. Several strategies are suggested for exploring what visual features may be used in low-level flight: systematic condensation of expert opinions, geometric analysis of terrain information, and

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Item 20 (Continued):

psychophysical analysis of visual processing modalities. Equipment requirements and problems in visual displays are also discussed in an appendix paper. The body of the report discusses the value and pitfalls of the various approaches and uses low-level flight to show how such approaches might be combined.

SUMMARY

Objectives

This effort had two objectives. The first objective was to promote interaction between vision-research scientists and personnel working on flight simulator research and development (R&D). The second objective was a set of recommendations regarding R&D needs and strategies that might be useful in developing more effective displays of visual scenes in flight simulation, particularly for low-level flight.

Background

In general, the development and use of visual displays in flight simulation have been dominated by engineering concerns. Equipment for simulating visual scenes has become highly sophisticated, but vision science has played a limited role in determining what visual information is presented in simulators and how. As a result, fundamental questions remain unanswered as to how to make the visual displays used in flight simulators most effective or appropriate for flight training.

Approach

A workshop was organized by the Committee on Vision of the National Research Council and the Operations Training Division of the Air Force Human Resources Laboratory (AFHRL/OT), Williams AFB, Arizona. This workshop was held in June 1980 at Williams AFB and was attended by vision scientists from the academic community, as well as personnel from industry and the military services who are engaged in R&D on visual displays for flight simulation. Following the workshop, members of the Committee on Vision identified key R&D issues and strategies.

Specifics

The two-day workshop began with presentations to familiarize participants with the visual simulation R&D at AFHRL/OT. This was followed by a tour of the wide-field-of-view computer image generation facility there. A second set of presentations informed the AFHRL/OT staff about complementary research activities in portions of the academic community.

A steering group then developed examples of specific R&D approaches that might help clarify several of the long-range issues confronted in visual simulation. Primary emphasis was given to low-level flight, in which the extraction of visual information from terrain features is crucial but not well understood. Several strategies were suggested for exploring what visual features may be used in low-level flight. Specifically discussed were: (a) systematic condensation of opinions, particularly those of pilots, (b) geometric analysis of terrain information, and (c) psychophysical analyses of visual processing modalities.

Conclusions/Recommendations

The workshop format promoted productive technical interactions among the participants. It was concluded that multiple R&D lines were needed to answer the fundamental questions about visual display requirements for flight simulation. A mixture of R&D approaches was recommended, ranging from short-term attacks on issues of immediate operational concern, to long-range investigations of fundamental issues. Need for greater attention to training issues was noted, since in many cases the best R&D approach to visual problems cannot be determined until training needs are specified.

PREFACE

The work reported herein was accomplished in support of the Air Force Human Resources Laboratory's Air Combat Tactics and Training Research Thrust. In order to effectively utilize flight simulators to support advanced air combat training requirements, significant improvements in the display of out-of-cockpit flight environments will be required. The purpose of this work unit was to focus existing expertise in visual science on the design of research strategies appropriate for resolution of major issues in visual simulation requirements.

This report is based on a workshop held in June 1980 to discuss problems encountered in visual simulation of flight and to explore ways of stimulating better research in this area. Low-level flight was chosen as a problem example for discussion of how various research strategies might be applied. This limited effort is not intended to be a comprehensive analysis of the problems encountered in visual simulation of flight, and there has been no attempt to lay out priorities for research. Such a comprehensive assessment would be an enormous undertaking requiring a much more broadly constituted group. Rather, the approach has been to attempt to give a sense of the complicated mixture of issues encountered in determining what visual display information is required for effective simulation of a given flight environment. Examples are presented to show how basic research perspectives might be used to attack these issues.

Individual research perspectives of some members of the steering group are included as appendixes to this report. The body of the report discusses general issues, suggests ways to facilitate interaction of basic scientists and simulation engineers, and attempts to show the complementarity of several approaches to research. The entire group discussed the body of the report, written by Whitman Richards with the assistance of Key Dismukes.

Robert Hennessy of the National Research Council and Stanley Collyer of the Naval Training Equipment Center substantially assisted the steering group with numerous discussions, suggestions, and identification of relevant literature. With some effort, they provided the steering group a quick education in the practical problems of simulation. George Buckland, the Air Force project officer for this study, played a major role in organizing the workshop on which this report is based. Lloyd Kaufman and Conrad Kraft made helpful comments on an early draft of this report and provided thoughtful suggestions about the problems of visual simulation research.

The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the federal government. The Council operates in accordance with general policies determined by the Academy under the authority of its congressional charter of 1863, which establishes the Academy as a private, nonprofit, self-governing membership corporation. The Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in the conduct of their services to the government, the public, and the scientific and engineering communities. It is administered jointly by both Academies and the Institute of Medicine. The National Academy of Engineering and the Institute of Medicine were established in 1964 and 1970, respectively, under the charter of the National Academy of Sciences.

This work relates to Department of Air Force Contract F33615-80-C-0009 issued by the Department of the Air Force, Air Force Systems Command. However, the content does not necessarily reflect the position or the policy of the Department of the Air Force or the government, and no official endorsement should be inferred.

The United States government has at least a royalty-free, nonexclusive, and irrevocable license throughout the world for government purposes to publish, translate, reproduce, deliver, perform, dispose of, and to authorize others so to do, all or any portion of this work.

TABLE OF CONTENTS

INTRODUCTION 1

BACKGROUND: PROBLEMS IN VISUAL SIMULATION RESEARCH 5

RESEARCH NEEDS 8

SOME STRATEGIES FOR RESEARCH 10

Introduction 10

Identifying Potentially Critical Factors by Pooling "Expert Opinions" 10

Information Analysis 12

Visual Psychophysics 13

Integrating the Three Approaches: An Example 14

Evaluation Vision Research 24

APPENDIXES

A. Analysis of Non-Metric Data - Derek Fender 31

B. Computational Analysis: Implications for Visual Simulation of Terrain - Kent Stevens 38

C. Visual Sensory Aspects of Simulation - D. M. Regan 65

D. Locomotion Through Visual Space: Optic Flow and Peripheral Vision - Ralph Norman Haber 72

E. Display Design Variables Pertinent to Low-Level Flight Simulation - Harry Snyder 82

F. Flight Simulator Workshop, June 1980 98

VISION RESEARCH FOR FLIGHT SIMULATION

INTRODUCTION

The U.S. Air Force Human Resources Laboratory (USAFHRL) asked the Committee on Vision to organize a workshop on vision research issues in flight-training simulators, particularly those using computer image generation (CIG) techniques. The workshop, held at Williams Air Force Base, Ariz., in June 1980, had two purposes. First, it was an experiment in facilitating interaction between vision scientists and personnel working on flight simulator research. Second, it explored research needs and strategies that might be useful in developing more effective display of visual scenes, particularly for low-level flight.[1]

In general, the development and use of visual displays in flight simulation have been dominated by engineering concerns. Equipment for simulating visual scenes has become highly sophisticated, but vision science has played a small role in determining what visual information is presented in simulators and the way it is presented. Vision scientists have done limited work on determining the information required for effective visual simulation. Well-controlled experiments to compare training effectiveness of different approaches to visual simulation are expensive, difficult, and time consuming, partly because they cannot be readily conducted in laboratories. Little theoretical work is available to predict the kinds of visual information that should be included in a particular simulation. Consequently, simulator designers and buyers have typically opted for as much "realism"[2] and display capability as possible, since the research literature does not provide a basis for selecting or evaluating simpler displays.

The two-day workshop (see appendix F for topics and participants) began with presentations to familiarize participants with visual simulation research efforts at the Operations Training Division of USAFHRL at Williams AFB and was followed by a demonstration of the wide-field CIG used for research there. A second set of presentations informed the Williams staff about complementary research activities in portions of the academic community. During the first day, it rapidly became obvious that an enormous number of research issues are involved in attempting to develop effective visual simulations. These issues include CIG techniques, the capabilities of the human visual system, information processing needs, attentional factors, measures of training effectiveness, and strategies for enhancing training (see table 1). But researchers have made little progress in isolating components of major simulation issues so that they can be attacked separately. Also, training needs apparently have not been sufficiently well characterized to allow visual requirements to be defined accordingly. This range of problems was clearly too large for a small group of vision scientists to address in depth in a single workshop. Thus, on the second day, the discussion concentrated on possible research strategies for determining what visual information is needed in a simulator for a pilot to perform a required flight task. The issues of training and simulator evaluation were set aside, although participants continually noted that these issues are important and deserve careful consideration (see next section).

---

[1] Low-level flight is defined as flying along the contour of the earth, usually at an altitude below 200 feet (above ground level).

[2] Realism is used here to include both accuracy (fidelity to real-world characteristics) and completeness of detail.

Visual scene requirements differ considerably among flight tasks simulated, and research needs will vary accordingly. A particular flight environment, low-level flight, was chosen as a problem-solving example for the second day of workshop discussion. This choice was based on several factors. Acquisition of basic flying skills, such as take-off and landing, has been shown to occur with simulation training, even with fairly simple visual displays (Semple et al., 1980; Waag, 1981). Much less is known about the visual requirements for simulating advanced tasks such as low-level flight for either initial acquisition or maintenance of skills. Low-level flight is an important Air Force mission, yet it has been difficult to simulate adequately with CIG systems. Even experienced pilots may misjudge altitude, range, and shape of the ground in simulators, problems that suggest that some unknown aspects of the visual display are inadequate to allow performance[3] comparable to that in the real world. Low-level flight may be a worst-case example in which visual demands are great and simulation requirements are not understood. Research approaches that help determine visual display requirements for low-level flight may also prove useful in analyzing visual requirements for other, simpler flight tasks.

After the workshop, the steering group met several times to discuss research issues and prepare this report. We do not intend this limited effort to be a comprehensive analysis of the problems encountered in visual simulation of flight, and we have not attempted to establish research priorities. Such a comprehensive assessment would be an enormous undertaking requiring a much more broadly constituted group. We have attempted to give a sense of the complicated mixture of issues encountered in attempting to determine the visual information required for effective simulation of a given flight environment. This report has two main parts. First, we will discuss the general need for

---

[3] However, see discussion in the following section of whether performance in simulators is an adequate measure of training effectiveness.

TABLE 1 Some Issues in Simulator Training Research

Training & Management Issues	Instructional Issues	Hardware Requirements
Tasks for Simulation Training	Role of Instructor	Visual System
Training Strategies	Task Difficulty Level	Motion Systems
Initial Training vs. Skill Maintenance	Augmentation of Feedback	A/C Dynamics
Whole vs. Part Task Training	Scheduling of Feedback	Instructional Features
	Adaptive vs. Fixed Amount of Training	Motion-Visual Synchronization
Knowledge-Based Issues	**Behavioral Issues**	**Visual & Display Issues**
Experimental Methodologies	Individual Differences	Image Quality
Performance Assessment	Attention and Workload	Image Detail
Application of Basic Research Findings	Skill Degradation	FOV Size
	Motivation	Realism
	Components of Skills	
	Perception	
	Cognition	
	Response Processes	

SOURCE: R. Hennessy, unpublished.

research in this area in a way we hope will convey the magnitude of the problems encountered. In this context, we will suggest ways to facilitate the research needed and to stimulate interaction between scientists and simulation researchers. Second, we will describe some of the technical problems in more detail, giving a few examples of applying basic research strategies to these problems. We have identified some areas of research that may be relevant to the simulation problems; however, these examples are not intended as a comprehensive list.

Individual authors developed the examples of research strategies as appendix papers for this report. We asked the authors to describe, preferably by example, the value and pitfalls of the particular research approaches they would pursue. These diverse approaches are complementary; we will attempt to show in the body of the report how they might be combined to address some aspects of the problem of simulating low-level flight. Some authors developed their approaches from a particular theoretical perspective; we will briefly discuss assumptions underlying these perspectives, but we will not debate whether they will eventually be proven correct. At this point in simulation research, the value of such theoretical orientations is in helping formulate sharp questions that will generate useful data.

Other examples of research approaches could have been chosen equally well for these illustrations. There is no one best research approach to a field as large and uncertain as visual simulation, even if one concentrates on a particular task simulation. Rather, a diverse mixture of research approaches should be encouraged. Indeed, the members of this small steering group represent a range of research perspectives, and each would attack these problems differently. The choice of these research examples is oriented toward the particular problems raised by low-level flight. For instance, several examples emphasize geometric aspects of terrain. Some or all of these research approaches might also be used to study simulation of other flight tasks; however, the emphasis would be different. We stress that effective research strategies must include an analysis of the particular features and requirements of the flight task to be simulated.

Simulation workers will note that most of these examples of research strategy differ from those typically found in simulation research literature. In contrast to simulation research focused on existing equipment, these examples of basic research address long-range issues of visual simulation. We have emphasized the fundamental side because that is the aspect for which the Air Force has the fewest resources and in which we are best able to assist.

BACKGROUND: PROBLEMS IN VISUAL SIMULATION RESEARCH[4]

Simulators are widely used for commercial, military, and space flight training. Simulation training has been shown to reduce substantially the number of actual flying hours required for student pilots to master basic skills and for experienced pilots to learn about new aircraft. In addition to reducing training costs, simulators can be used to train pilots safely in hazardous maneuvers and to create situations that do not occur or cannot be adequately controlled in the real world (Hennessy, 1981).

Rapid improvements in computer image generation (CIG) techniques in the past decade have resulted in fairly sophisticated visual displays for simulation. Nevertheless, the contribution of visual displays to overall training effectiveness of simulators is poorly understood. A few studies have systematically examined effects of visual display features on training effectiveness (see, for example, Semple et al., 1980; Waag, 1981). Concern about visual display effectiveness is being raised, particularly among military R&D personnel, because of several developments, especially the following:

1. The costs of advanced simulators are rising rapidly. Visual simulation has been pushed to provide all the realism and capability afforded by rapid advances in technology, with attendant rises in cost.
2. Some researchers have questioned the value of realism as a guide for visual display (see, for example, Coblitz, 1980; Hennessy et al., 1980).
3. Simulation of advanced flight maneuvers and environments, such as low-level flight, has been found to be problematic. The adequacy of training in existing simulators for low-level flight and other visually demanding tasks is not clear from the few existing studies.

The development and use of visual displays in simulators have been dominated by engineering considerations.[5] Visual scientists and psychologists have played only a minor role in deciding what visual information should be displayed and how. Design engineers have developed visual displays based on common sense and previous experience. The major criterion of adequacy of displays has been their degree of acceptance by experienced pilots. The evaluations of both pilots and designers appear to be based largely on how realistic visual displays appear, rather than explicit consideration of training effectiveness.

The contributions of visual scientists have been limited, largely because they have not been able to tell designers the kind of information that visually displayed scenes should contain. Our knowledge of higher-order perceptual processes is too limited to specify with certainty the forms in which visual information is extracted by pilots performing particular tasks in the real world. Uncertainty about both visual information processing and perceptual and cognitive factors in training makes it difficult to devise coherent strategies for display of visual information in simulators. So far, the contribution of vision science to simulation research has been primarily in the area of image quality (resolution, contrast, distortion, etc.). Psychophysical studies (e.g., Kraft et al., 1980) of human visual sensitivities have provided information needed by engineers attempting to design displays to match human capabilities.

---

[4] For more extensive discussions, see Brown (1976), Hennessy et al. (1980), and Semple et al. (1980).

[5] For more extensive discussion of this issue, see Boff and Martin (1980), Fulgham (1978), and Hennessy (1981).

Semple et al. (1980) point out that because of this uncertainty about visual information requirements, it has probably been reasonable for designers to emphasize development of visual displays with maximum detail and fidelity. No evidence, however, supports the common assumption that increasing realism improves the training value of simulators (see also Waag, 1981). Furthermore, highly realistic display of extended terrain for missions such as low-level flight is not possible with existing CIG equipment, and there may be inherent limitations to display realism (see appendix B).

Training issues are beyond the scope of this report and the competence of its authors; however, visual display issues must be considered in the context of training requirements. Training simulators may be used for acquisition of basic flight skills by student pilots, for transition to other types of aircraft by experienced pilots, and for proficiency maintenance in a given aircraft. Visual display requirements may differ considerably among these three training roles and with different flight tasks. For example, acquisition of basic skills has been shown to be substantially enhanced by simulation training with simple and in some cases highly unrealistic visual displays (Hennessy et al., 1981). In contrast, proficiency maintenance of visually demanding tasks might require more detailed visual presentation; however, in the absence of data we can only speculate on this point.

Collyer has suggested (private communication) that three kinds of skills are acquired in flight training:[6]

1. Perceptual: "When the world looks like this, what is the aircraft's situation?"
2. Decision/procedural: "When the aircraft is in this situation, what needs to be done next?"
3. Control: "How do I make it do that?"

Traditionally, flight instruction has emphasized procedural and control skills; little attention has been given to perceptual skills, and in fact little is known about perceptual learning processes in flight training. It may be that the demonstrated effectiveness of simulators in training basic flight skills results mainly from learning procedural and control skills, and in this case the degree of realism of the visual display may not be very important. Perceptual learning might play a larger role in learning and/or maintaining proficiency of some flight tasks than in others. Resolution of this issue would facilitate cost-effective design of simulators for specific tasks. Unfortunately, there has been little good research on this point, although some recent studies appear promising (e.g., Coblitz, 1980; Hennessy et al., 1981).

---

[6] Also see Roscoe (1979) on this point.

The ultimate measure of simulator training effectiveness is the enhancement of actual flight performance. Unfortunately, transfer-of-training studies are difficult and costly, and they must compete with operational missions for pilots and equipment. Although transfer-of-training studies have demonstrated effectiveness of simulator training for a number of tasks, almost none of these studies has been designed to reveal the contribution to training transfer of the different features of the equipment and simulation instruction (Waag, 1981). Thus we have virtually no empirical information on how transfer of simulation training is affected by visual display characteristics or by the information content of the visual scene. Several investigators have suggested that instruction methods used in simulator training may have as much or more impact on effectiveness as do equipment features (e.g., Caro, 1977).

Transfer-of-training studies that simultaneously evaluate effects of several simulator equipment features, trainees' characteristics, and training procedure variables are urgently needed (Simon and Roscoe, 1981). It would also help to have techniques for predicting simulator training effectiveness, to be used to determine which issues, procedures, and equipment warrant full-scale transfer studies. Pilots' performance in the simulator has been used as such a measure (e.g., Westra et al., 1981). This measure, however, is problematic. Factors that affect performance in the simulator may not have the same effect on transfer of training. Platform motion, for instance, in some studies improved pilot performance in the simulator but did not affect transfer to actual flight performance in these and other studies (e.g., Waag, 1981). It is sometimes assumed that factors that do not influence performance in the simulator will not contribute to transfer of training; however, this assumption needs careful analysis and experimental evaluation.

A major problem with most transfer-of-training and performance studies is that their designs do not allow generalizations to be drawn. In addition to not discriminating among effects of different simulation factors, most studies have too narrow a focus (e.g., studies on a particular piece of equipment or a specific operational need) to shed light on the general questions about visual information requirements. These studies are not additive. In contrast, the work of Westra and coworkers (1981) and Simon and Roscoe (1981), among others, suggests possibilities for developing more powerful empirical methods of evaluation.

In summary, evaluation studies have demonstrated that visual simulation can substantially enhance training of some (but not necessarily all) flight tasks. There is, however, little information on the relative training effectiveness of different approaches to visual information display. Virtually nothing can be said with certainty about the best way to display visual information for simulator training of particular tasks.

RESEARCH NEEDS

As pointed out earlier, empirical studies of the relative training effectiveness of different approaches to visual simulation have been quite limited. On the basis of either existing evaluation studies or theories of visual perception, it is impossible to specify with any certainty the visual information requirements for simulation training of specific flight tasks. Simulators in use today provide effective training of some, not all, flight tasks; however, it is important to consider cost effectiveness as well as training efficacy (Orlansky and String, 1977). Lack of knowledge of visual information display requirements makes it difficult to maximize training effectiveness or minimize costs.

Research on visual information requirements for simulation training has lagged for several reasons. The difficulty and cost of performing transfer-of-training studies and the incompleteness of knowledge of visual perception have been mentioned earlier. Little good theoretical work has addressed visual simulation problems. For instance, little progress has been made in understanding geometric aspects of information extraction from terrain viewed by pilots since Carel's (1961) research. Work is limited in this field in part because few CIG simulators are available for research. Recently, researchers have used two simulators with modern visual systems: the Advanced Simulator for Pilot Training (ASPT) at Williams Air Force Base, Ariz., and the Visual Technology Research Simulator (VTRS) at the Naval Training Equipment Center in Orlando, Fla. Personnel at these two facilities have made notable efforts to deal with some of the research issues described herein, but clearly a much larger enterprise is required to resolve these problems.

A comprehensive analysis of research needs and priorities in this field is beyond the scope of this limited study[7]; however, some general observations may be useful. No one line of research can answer the questions raised in this report. A mixture of research approaches is needed, ranging from short-term attacks on issues on which operational decisions cannot be delayed to long-term studies of fundamental issues of information extraction from terrain features. Research is required for both visual information requirements and training issues. Much attention should be given to designing research methods so that knowledge gained from diverse studies will be additive instead of applicable only to the particular simulation and equipment used in each study.

The broad issues of visual simulation requirements need to be broken into discrete components that are potentially solvable. This task alone will be no small feat. Current research attempting to define relationships between visual simulation variables and flight control performance has immediate value for evaluating specific displays and equipment features, but it will not provide fundamental knowledge that is cumulative and that might allow prediction of visual information requirements for a wide range of simulation training tasks. Vision scientists in academia may be able to help devise improved research approaches. This effort will require, however, long-term commitment of these scientists to simulation issues and availability of facilities for such work.

---

[7] See Hennessy et al. (1980) for one such effort.

Effective research on visual simulation requires work in both laboratory settings and simulator facilities. In both settings, more interaction between basic scientists and simulation engineers is needed. Most vision scientists in academia are not familiar enough with flight simulation problems to be aware of how their research might be applied. Simulation studies appear mainly as technical reports, rather than in the journals widely read by vision scientists, and are relatively inaccessible to the academic community. Furthermore, few meetings are held for simulation engineers and vision scientists to exchange information and ideas. The human factors area, in which such interchange is fairly common, might be a good model for interaction of vision science and simulation study.

To improve and stimulate information exchange between the academic and simulation communities, the steering group suggests increasing use of three kinds of mechanisms:

1. Conferences: The recent Image II conference illustrates the value of forums for interaction of vision scientists and simulation engineers.* Direct person-to-person confrontation is the most rapid and effective way to become aware of and understand the pressing issues of the moment. (As an aside, state-of-the-art tutorials in relevant areas of science might be considered for part of these conferences.) Such meetings need to be held regularly to ensure the continuing involvement of the scientific community. Also, special sessions in flight simulation could be encouraged at existing meetings of scientific societies. Such sessions have the potential of reaching broad segments of the vision community. The annual meetings of the Human Factors Society have included such sessions profitably, and a session on visual simulation was held at the October 1981 meeting of the Optical Society of America. Other societies that might be asked to include sessions on simulation include IEEE, the Society for Information Display, and the Psychonomics Society. National Research Council symposia, such as those organized by the Committee on Vision on applied visual problems, could also be helpful.

2. Proceedings and Review Articles: Proceedings serve the obvious function of providing information about the content of a meeting to those who were unable to attend. Unfortunately, proceedings of simulation conferences have not always been widely available. Publishing proceedings in a journal is probably the most satisfactory way to disseminate this information. Some consideration also should be given to preparing annual reviews of vision research relevant to simulation (for engineers) and of simulator display capabilities (for vision researchers).

3. Exchanges: Although training fellowships exist that allow scientists in academia to visit and collaborate at simulator facilities, the availability of such fellowships is not generally known in the academic community. Greater effort should also be made to provide opportunities for simulator personnel in federal agencies to visit or study in university laboratories. Two existing mechanisms that should

---

* Monroe, E.G. 1981 Image II Conference Proceedings. AFHRL-TR-81-48, AD-A110 226. Williams AFB, AZ: Operations Training Division, Air Force Human Resources Laboratory, November 1981.

be more widely advertised and utilized for simulation research are the NRC postdoctoral fellowship program and the Intergovernmental Personnel Act. The provisions of this act allow for exchange of senior scientists, which is crucial. Reserve Officers' Training Corps (ROTC) programs might be broadened to attract science graduates for military research on simulation.

The comprehensive research program needed for simulation issues to be resolved would obviously be expensive and would have to be considered in terms of potential costs and benefits. Simulator training affects both operational readiness and pilot safety. Current investment in research on vision and training issues is apparently small in comparison to the projected size of simulator procurement programs (several billion dollars).

SOME STRATEGIES FOR RESEARCH

Introduction

Appendixes A through F provide examples of research areas and approaches that might help elucidate several long-range issues confronted in visual simulation. Primary emphasis is given to low-level flight, in which extraction of visual information from terrain features is crucial but little understood. Several strategies are suggested for exploring which visual features should be used in low-level flight: systematic condensation of opinions, particularly those of pilots (appendix A), geometric analysis of terrain information potentially usable (appendix B), and psychophysical analysis of visual processing modalities (appendixes C and D). Appendix E examines equipment requirements for display of whatever visual information is chosen. It also addresses characteristics of visual displays that limit the kind of information that can be displayed. Thus, appendix E complements the other appendixes and is applicable to simulation of any flight environment. Several of these authors have suggested particular lines of research that could be followed within their paradigms.

The next section of this report summarizes the theoretical perspective and working assumptions of these strategies to illustrate their power and limitations. An extended example is given to show how these strategies might be combined to analyze visual information requirements for low-level flight. The complementarity of these research strategies is emphasized.

Identifying Potentially Critical Factors by Pooling "Expert Opinions"

The subjective opinions of design engineers, pilots, and visual scientists have played a large role in selecting the visual features displayed in flight simulators. Many attempts to identify the visual factors or cues that are important for a given flight task have begun with a subjectively composed list of scene parameters (e.g., field of view, spatial resolution, luminance, color, representation of landscape, horizon, clouds, shading, known terrain features, shadows, aerial perspective) and perceptual factors (e.g., binocular vision, accommodation, motion, shear) (Brown, 1976; Gibson, 1950; Kraft et al., 1980). The many attributes and factors on these lists may be subjected to experimental study, but often they are simply rank ordered subjectively and incorporated into equipment design without empirical evaluation.

This procedure has several flaws. Some pilots may have useful insight about the visual cues they use in given flight maneuvers (e.g., Langewiesche, 1944), but this insight is generally far from adequate for characterizing vision information requirements for display. Furthermore, pilots' impressions of the information they use are sometimes wrong (see, for example, Waag's (1981) discussion of pilots' evaluations of platform motion). Casual ranking is not a powerful method of analyzing opinions, and it is difficult to combine systematically the opinions of a large number of raters in this way.

Although pilots' opinions are inadequate for determining visual display requirements, they may be highly useful in identifying features that can be studied experimentally. More effective analysis of pilot opinions could be achieved with non-metric scaling techniques. One example of these techniques, KYST, is outlined in appendix A. To summarize KYST, a jury of knowledgeable persons is asked to create a list of all the scene attributes they believe apply to a particular flight task, in this case low-level flight. Pairs of these attributes are then evaluated as to their importance for this flying task. From these ankings, a multidimensional space is created in which all the attributes are located in terms of their importance relative to one another. This space can then be reduced by factor analysis, with the result being a measure of how many dimensions are needed to capture the factors that underlie all the attributes (Hake and Rodivan, 1966; Kruskal and Shepard, 1974). Although these common factors may not be identified, the analysis is important because it will show which factors might be rejected and which need to be considered seriously, qualitatively indicating their common characteristics.

Working Assumptions

If a visual factor is missing from the original list subjected to KYST analysis, it will of course not appear in the final analysis. This absence, however, does not impede relative ranking of the factors that are listed; furthermore, additional factors can be added for reiterative analysis. Multidimensional scaling techniques do not require that the list of "cues" or factors be exhaustive. So long as at least one item on the list of attributes captures a dimension of relevance, then that dimension will be identified. The major drawback of this technique is that the pair-wise ranking procedure still depends on subjective evaluations. Pilots may be unaware of their use of some factors and may make unwarranted assumptions about the importance of others. Nevertheless, pilots undoubtedly have much relevant expertise that is hard to draw on adequately without some sort of systematic analysis such as KYST. By suggesting areas for experimental study, this kind of analysis complements other research approaches.

Information Analysis

The information analysis approach attempts to define the visual information requirements needed to perform a flight task. For example, during low-level flight, the pilot must judge altitude accurately while flying over arbitrary terrains. Is it computationally feasible to use stereopsis to solve this problem? If not, which sources of information could, at least in principle, provide sufficient data for reliable low-level flight? Is it practical to present this information in a CIG display? Appendix B gives an example of this approach, showing that the pilot must extract three types of information about the terrain from the display: shape, scale, and orientation. The analysis continues by illustrating which simple features in a CIG display could provide this information and the assumptions the pilot (unconsciously) must make when using these two-dimensional image features to make three-dimensional (3-D) inferences.

Working Assumptions

Information analysis assumes that the particular forms of 3-D information that the pilot extracts from the CIG display may be individually isolated along with the visual processes that extract the information. It is further assumed that those processes place constraints on the interpretation of the display, and that these constraints may be discovered. These constraints are provided by certain geometrical properties of surfaces and perspective projection. Human vision must make assumptions about the real world in order to interpret the ambiguous visual information that it receives. When such assumptions are wrong in some situations, the perception does not correspond to reality.

The flight simulator generates 3-D images from an internal model of a 3-D environment, and the pilot's visual system processes these images with implicit assumptions about the nature of that environment. If the pilot's 3-D perception of the scene is to coincide with that which was intended, then it is necessary that the geometric structure of the model, and the way it is portrayed by CIG, obey these perceptual assumptions. To give a simplistic but illustrative example, we often assume that intersecting straight lines meet at right angles in 3-D, provided there is no evidence to the contrary. That assumption helps constrain the 3-D interpretation of intersections in an image. But if the internal model of a corner of a field or runway is other than a right angle (imagine that the runway is a trapezoid), then the viewer will be misled. We usually have several independent ways of determining the 3-D shape, hence misinterpretation is not a serious problem in natural scenes, with all their richness and redundancy. But in the impoverished scenes of a simulator, it is important to have the model's geometry coincide as much as possible with that expected by the visual system. Consequently, we must understand the computational constraints (geometric and otherwise) that underlie the solution to a vision problem in order to formulate precisely design rules that govern scene generation and lead to consistent and accurate 3-D interpretations.

Visual Psychophysics

Short-Term Experimentation

Multifaceted experimental analyses (e.g , Westra et al., 1981) are useful for evaluating the relative effects of identified variables on performance in simulators or on transfer of training. These studies are particularly helpful in assessing the importance of the differences between subjects relative to the simulator variables, but they usually offer little insight into the origin of the individual differences. If different pilots rely heavily on different informational aspects of the display, then this knowledge may be lost in a factor analysis. To understand the degree to which each source of flight information can be utilized by a pilot, long-term psychophysical studies must be conducted.

Long-Term Experimentation

Another distinct methodology examines certain perceptual abilities in detail. The goal is to derive a quantitative understanding of the behavior and capabilities of the human visual system. Although much of psychophysics has dealt with the resolving power of the visual system (spatial and temporal), much recent effort has concentrated on understanding particular "modules" of the visual process, such as stereopsis, texture, motion, and looming. By understanding the capabilities of various "modules," their utility for a particular flight task can be evaluated.

Studies in color vision provide a good example of the value of the modular approach. More than a century ago, psychophysical experiments demonstrated that the human color vision system behaved as if it analyzed spectral information using only three color filters or "channels." This property of the eye subsequently was exploited in color photography and makes possible practical color television (as well as CIG color displays). By coding the signal characteristics to match those of the "channels" of the human color system, all the useful information about the spectral content of the scene is delivered economically and effectively with a tremendous economy in bandwidth. More recent work in vision suggests hints of other such modules (Richards, 1980), some of which may be especially important for flying tasks. Appendixes C and D illustrate this approach, emphasizing how simple tests may be developed to isolate and dissect a particular module and to assess individual differences. The example in appendix C compares sensitivities of motion-in-depth and size changes, both of which are potent sources of information useful to low-level flight.

Working Assumptions

The crucial assumption that distinguishes a multifactor approach from a modular one is that the modular approach assumes that the visual ability under study is mediated by a substantially independent visual process. In psychophysical terms, a module (or set of channels) processes information independently of another set of channels (i.e., movement or size change). This assumption is imposed by methodological pragmatics--there are analytic means for studying simple processes of few parameters. If there were dependence on other visual processes, the analysis would become intractable.

A second assumption common to both psychophysical approaches is that the visual ability under study is relevant to the task of flying an aircraft. This assumption is made initially, when first studying the ability, but later that assumption may or may not be verified. The quantitative understanding gained through psychophysics may in fact demonstrate that the ability is irrelevant to the task of flying. On the other hand, because of perceptual sensitivity, the ability may predict special relevance, which may then be verified in a transfer-of-training study.

The third assumption, the requirement for approximate functional independence of different modules (at least at the early levels of information processing), places limitations on the range of visual abilities that are amenable to complete psychophysical study using a modular approach. At some stage of visual processing, the interactions among the individual processes become significant, and at that point any modular analysis by psychophysics becomes infeasible.

Integrating the Three Approaches: An Example

Minimal Information

One approach to designing a simulator is to analyze the minimal information needed to perform the real-flight task.[8] For example, if it is necessary to judge altitude at some point during visual flight, there must be adequate information about altitude in the visual scene. Although the minimal information required for simple flying maneuvers such as horizontal flight or landing may be obvious, one of the difficulties with simulating low-level flight is that this minimal scene content is not known. Here intuition is not an adequate guide, for even experienced pilots have difficulty in isolating and formalizing what is needed in the display (Hennessy et al., 1980). A non-metric multidimensional scaling analysis could be a useful first step in identifying relevant attributes of the environment encountered during low-level flight. The outcome of such an analysis of expert opinion should suggest the kind of information required by the pilot to fly at low altitudes. For example, if an adequate representation of the ground plane and horizon is suggested as belonging to one important dimension of the analysis, then presumably the pilot needs to know his orientation with respect to the ground plane for successful low-level flight. If "known human object size" or "shadow" appears on another dimension, then this result might suggest that it is necessary to provide some calibration of the scale of the terrain so that altitude can be judged reliably.

---

[8] This example is concerned with flight performance in the simulator. As previously discussed, we do not know how closely performance in the simulator must follow real-flight demands for low-level flight to accomplish transfer of training. The minimum information approach is conservative in the sense that it should provide an adequate visual display for learning skills that can be transferred to real flight. We do not preclude the possibility of demonstrating transfer of training with very simple visual displays, even with low-level flight (see previous discussion of learning of perceptual and control skills). Such empirical demonstrations, however, may be difficult to generalize from one simulation to another.

We will assume for the purposes of this illustration that preliminary analysis has suggested that the visual scene in low-level flight provides at least three kinds of information: (1) impact point and time, (2) altitude, and (3) depression of flight angle with respect to the ground.

Informational Analysis

The central problem of low-level flight is to maintain some specified height above the ground (or to fly within an altitude band). More specifically, the task is to estimate the altitude above the ground, $\underline{A}$, and flight path angle β of the aircraft[9] at some future time $\underline{t}$ and distance $\underline{D}$, where the time $\underline{t}$ is sufficiently long to allow a corrective maneuver to be made. Figure 1 depicts this simple situation, in which the aircraft must fly within an altitude band $\underline{E}$ over hilly terrain. If the pilot has complete knowledge of the performance of the aircraft (e.g., its climb or descent rate), one can specify the minimally curved flight contour within the band $\underline{E}$ (dotted line).

The problem as outlined above is still formidable and must be broken down into simpler components. Reviewing the goals of low-level flight, it is clear that the minimal objective is to avoid hitting the ground. Perhaps the next and more difficult step is to specify the visual information needed to clear the peaks, without regard to accurate altitude. Finally, the information requirements for a specified altitude objective for clearance can be sought, and flight within an altitude band can be considered.

A breakdown of the problem suggests the following states of analysis:

---

[9] Note that the flight path is not generally the same as the pitch (or angle of attack) of the aircraft.

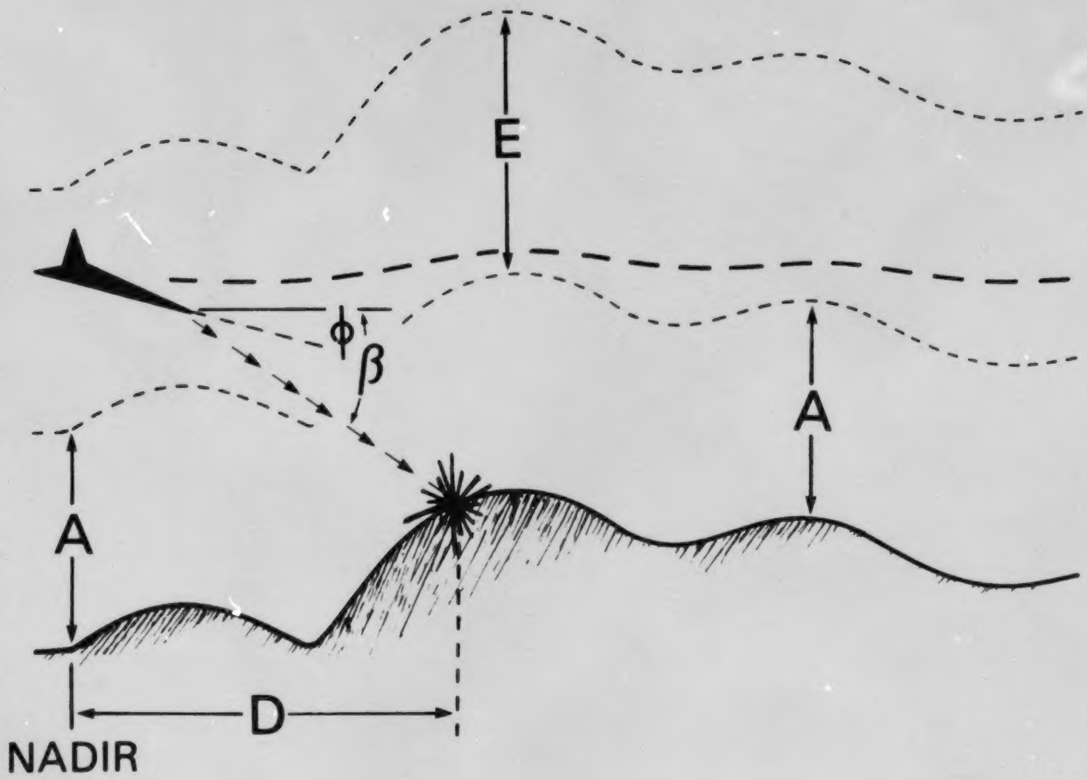


FIGURE 1 Depiction of low level flight task. A = minimum altitude above ground; β = flight path angle; ϕ = pitch angle (attitude). Cross-hatching indicates desired flightband; heavy dashed line is minimal flight path.

1. Derive the point and time of impact for the current flight trajectory.
2. Specify the minimum information needed to calculate depression angle of flight.
3. Specify the information needed to clear peaks.
4. Specify the information needed to clear peaks at 200 feet +/- 100 feet.
5. Analyze minimal conditions needed to fly over special terrains within an altitude band.
6. Extend item 5 to arbitrary terrains and flight conditions.

We will now use the derivation of the impact point and time as an example of an information analysis.

Deriving Point and Time of Impact Deriving the point and time of impact is relatively straightforward, provided that a velocity field of sufficient spatial and temporal resolution is present. (This is the "looming" cue investigated by Regan and Beverley, 1980, and Regan et al., 1981.) The impact point is simply the source of the flow field, as pointed out by Gibson (1950) and analyzed by Carel (1961).[10] The time of impact $\underline{t}_{\text{-impact}}$ is given by

$$\underline{t}_{\text{-impact}} = \theta/\dot{\theta} \qquad (1)$$

where $\dot{\theta}$ is the radial flow rate at eccentricity θ as seen by the observer.[11]

To solve equation 1 and to determine the source of the velocity field, texture and contour information must be displayed at densities and rates compatible with the performance of the aircraft and skills of the pilot. To explore these visual requirements, we can examine the information content needed to determine impact time.

Figure 2 plots the flow rate versus retinal eccentricity for various impact times. A log scale has been used to make the curves straight lines. For example, consider a time to impact of 500 milliseconds (ms), which might roughly represent the pilot's reaction time. Figure 2 shows that for $\underline{t}$ = 500 ms, flow rate changes from 1/4 to 20 degrees/second

---

[10] Llewellyn (1971) and appendix C report evidence that human observers cannot identify the source of the optic flow field. However, as Harker and Jones (1980) point out, in flying the task is not to identify the point (center of expansion) that does not move, but rather to select a point and keep it from moving. The observer conceivably may use other sources of information to stabilize the expansion point and then extract flow rate information.

[11] For simplicity of illustration, the special case of approach to an object lying in the observer's frontal plane is used. For the more general case of approach to a slanted plane, equation 1 would have to include terms for the effects of foreshortening.

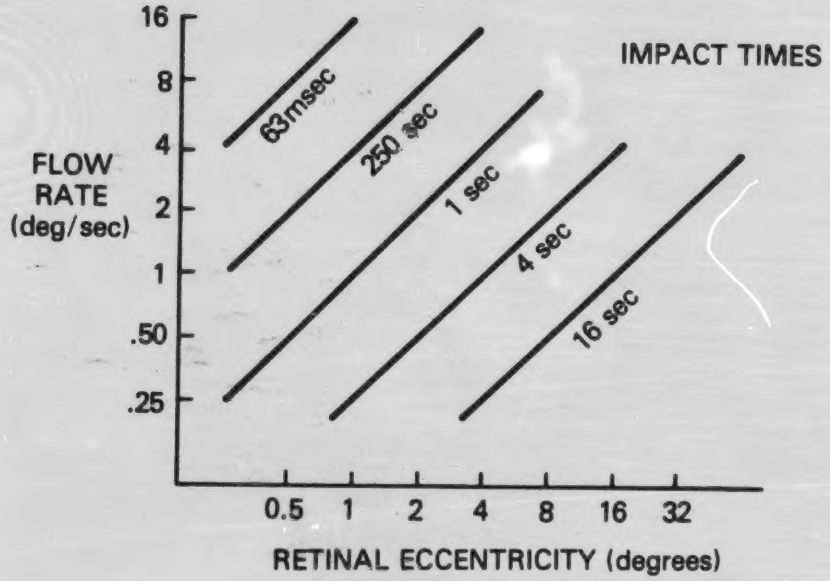


FIGURE 2 Flow rate versus retinal eccentricity for several impact times.

(deg/s) in the central 1/8 to 10 deg (this is within the range of human visual sensitivity to motion). If the display is a 1-meter (m) diameter CIG with a 30-ms update rate and a 1,000-line interlaced raster at 1 m, then the fastest motion that can be generated without skipping a raster line is 6 deg/s. Thus, to utilize a 500-ms reaction time capability, texture contours would have to occur within 3 deg eccentricity. One might want to provide perhaps ten times this contour density (i.e., 3 cycles/deg) in the visual display to allow effective estimation of flow rate and angle. Without this display capability, the simulator will not provide all the useful information offered by equation 1. (See appendix E for other design considerations.) (As an aside, we note that this stringent display requirement is needed only at the center of the display. Since the peripheral display requirement is much less severe, peripheral edges might be traded for central ones, in some graded manner according to figure 2 and human abilities.) This allocation of "center" of course would depend on where the pilot looks.

The above is an example of how an information-theoretic analysis aimed at designing a display to help the pilot avoid impact should proceed. If sufficient information about the time of impact is not displayed, the pilot might adopt a conservative strategy, such as always keeping the flight path above the terrain, but this strategy precludes controlled terrain following. Is this conservative behavior, elicited by the inadequacies of the simulator, the best training for the pilot? If it is not, then the capabilities of the simulator should be upgraded to provide at least the minimum information content needed to compute impact point and time.

Information Needed to Clear Peaks[12] To hint at possible solutions to the increasingly difficult stages of the problem, we briefly consider some additional information for clearing peaks.

Note that if the sky is textureless, then the source of the flow field must be inferred from the flow pattern of the terrain contours. Once again, therefore, an analysis of the display requirements should be made to ensure that the terrain content does indeed provide sufficient spatial resolution and detail to allow such an extrapolation to be made.

Without such information, a pilot is forced to look for other cues as to direction of flight. One possibility is to direct the aircraft so that the peak of the nearest hill is aligned with the next most distant peak.[13] However, without an adequate velocity field, neither the clearance altitude nor the time of arrival at the peak can be recovered. Again, an information-based analysis similar to that described earlier can specify the minimal display conditions, given the aircraft performance and the reaction times and visual abilities of the pilot.

---

[12] For suggestions regarding the extraction of altitude, see Harker and Jones (1980).

[13] Note that the alignment of the aircraft with a near ridge and the next peak is a good strategy for ensuring that the flight path angle is negative with respect to the ground plane.

Terrain Following Finally, if the full mission is to fly in the band E of figure 1 as originally proposed, then clearly the pilot must be able to perceive terrain shape fairly accurately. At present, it appears that the information required to do this is beyond reasonable technical capability, given the demands of low-level flight and the present optical and computational limitations of the available graphics displays. However, a computational analysis could profitably explore the possibility of a sufficiently rich display region for the lower portion of the display. Such a region might include only a small fraction of the total display field, allowing the possibility of at least an order of magnitude increase in texture content in a critical visual sector with little loss elsewhere. (See appendix D for other field-of-view considerations.)

Summary of the Approach The design of an optimally efficient simulator display requires an information analysis of the task that keeps in mind the performance of the aircraft, the visual abilities of the pilot, and the display capabilities. The formal steps in such an analysis are as follows:

1. A clear statement of the ultimate objective (task).
2. The subdivision of this objective into the component problems, from the simplest to the most complex.
3. An analysis of the minimal information requirements needed to solve the simplest problem.
4. An extension of this analysis to the more complex cases, showing how the required variables can be extracted from the displayed scene.
5. Consideration of the display and human capabilities that limit the available ranges of the variables of interest.

Applying Psychophysics

The non-metric scaling technique is designed to suggest which aspects of the environment are important to a task such as low-level flight. The information analysis then shows what must be included in a two-dimensional visual display of the simulator to allow a pilot to extract this information. However, because the results of each approach depend on certain assumptions, it is necessary to demonstrate that the observer does indeed have the ability to sense this information with sufficient accuracy. For example, a high-resolution binocular visual system can, in principle, recover a complete 3-D terrain map and hence reveal distances, slopes, altitudes, and velocities. The threshold for human stereoacuity, however, limits the range of binocular vision to distances that would be covered by a high-speed aircraft in seconds. A critical component of the analysis of a problem to be simulated is to ensure that the displayed information is not only relevant but useful. At the same time, psychophysical studies of the parameters of interest have the potential of foretelling whether one individual will perform better than another on a well-defined and understood task (Regan et al., 1981). We will illustrate these points using the simplified low-level task of deriving the time for impact. (For additional experimental suggestions regarding the position of impact (or flight direction), see appendix D.)

Time to Impact Time-to-impact information is contained in the optical flow field, but can the human observer use this information? If so, is all the information processing capability of the observer utilized in the simulator? A simple experiment by Carel (1961) suggested that time to impact can indeed be estimated as predicted from equation 1, without knowledge of the distance to the surface, object size, or speed. In this laboratory study, with an expanding flow field of random dots, subjects could easily make extrapolations to the time to impact when the field expansion was stopped before simulated impact (see figure 3).[14] The range of judgments is substantial, however. Is this range due to a limitation of the apparatus or laboratory setting, or is it an inherent inability of the human visual system? To answer this question requires further psychophysical study that fits nicely into the module or "channel" approach.

Size-Change Channels Referring again to figure 2, we note that the critical information about time to impact is conveyed by a change in angular size at a given eccentricity. To solve equation 1, we must either be able to measure both the rate of change in angular size, $\dot{\theta}$, and the retinal eccentricity, θ, and then take the ratio or measure $\theta/\dot{\theta}$ directly. For illustration, we will assume that the human observer can reliably recover θ and examine the psychophysical constraints imposed on displaying and using the derivative $\dot{\theta}$, recognizing that the more useful parameter[15] might be $\theta/\dot{\theta}$.

Human capability of measuring size change ($\dot{\theta}$) has been studied by Regan and Beverley (1979). Figure 4 shows threshold response data that Regan and Beverley discuss in terms of tuning characteristics of a size-change channel. Optimal sensitivity for all three observers is near a rate of 3 Hz for 1/4 min arc, corresponding to a velocity of 1/80 deg/s. (A more conservative threshold rate estimate for most of

---

[14] This does not imply that the observer necessarily could identify the point of impact from the flow field (see footnote 10). Furthermore, ambiguous and erroneous perception of expanding patterns is possible, as illustrated by the Ames trapezoid illusion. Even with full optical flow patterns, what is perceived may depend on the state of the observer, particularly when the scene content is impoverished in other respects. Further experimentation is needed to relate these laboratory data to visual simulation (e.g., Harker and Jones, 1980).

[15] To test whether the human observer uses $\dot{\theta}$ or $\theta/\dot{\theta}$, one can compare the combined variance for estimating θ and $\dot{\theta}$ separately with that for estimating the ratio $\theta/\dot{\theta}$.

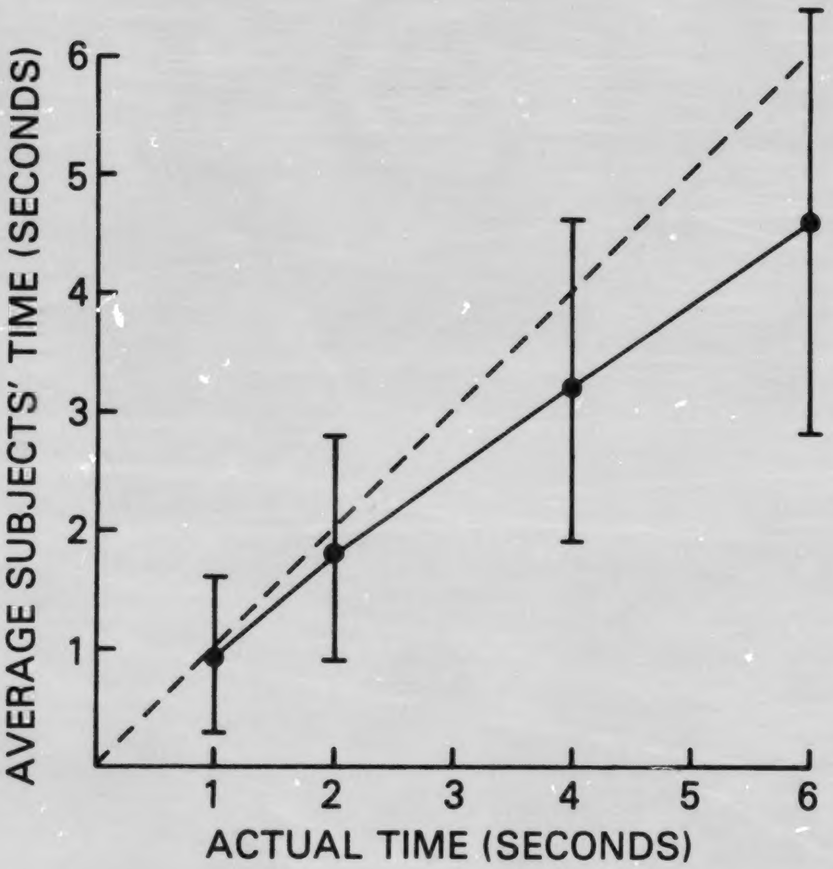


FIGURE 3 Carei's (1961) data for the reliability of estimating impact time.

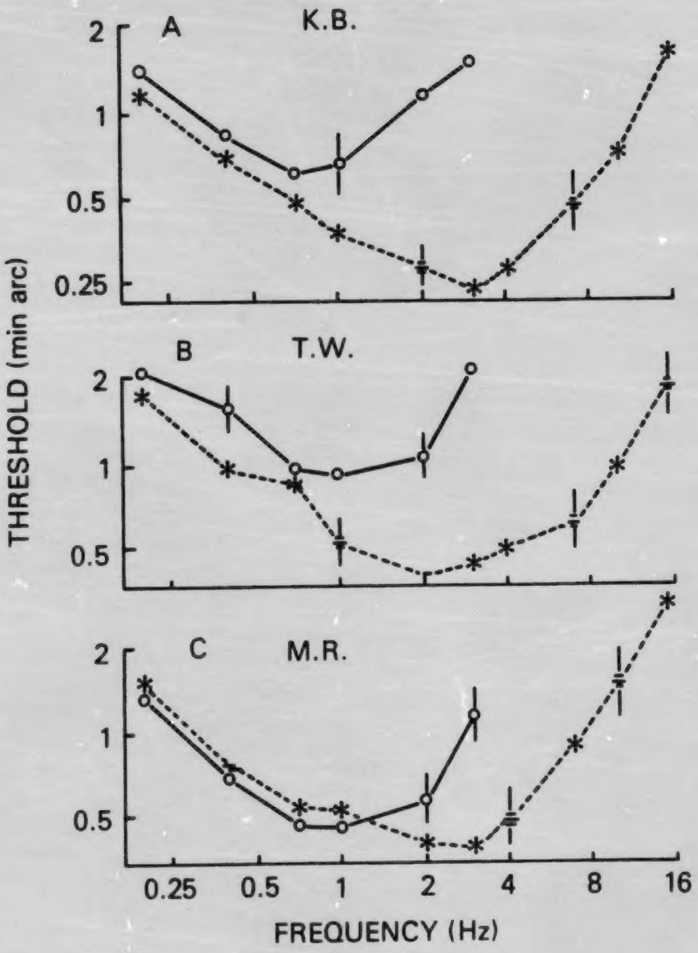


FIGURE 4 Tuning curves for size-change "channels" (adapted from Regan and Beverley, 1979). Dotted line = changing-size stimulation producing a size-change sensation; solid line = changing-size stimulation producing a motion-in-depth stimulation.

the frequency range would be 1/10 deg/s.) If the full capability of the human observer is to be utilized to extract impact time from rate change, then both the raster size and rate must meet these limits. For a 450 raster-line display at 1 m, the raster would be 10 lines per degree per meter of display. This translates into 6 min between raster lines for a 1 m display, so 1/25th m display diameter would be required if the full capability of the human observer is to be used to solve for time of impact.

Similar psychophysical constraints can be determined to set an upper bound on the detectable change in size, using the readily available spatial-temporal contrast sensitivity functions (Kelly, 1979; Wilson and Giese, 1977). Since these functions change with retinal eccentricity, so will the limits for the useful flow rates.

Figure 5 illustrates how human capabilities might restrict the range of flow rates that are useful for calculating impact time. The minimum spatial resolution for the human observer is also included to show how the available flow rates are restricted to a portion of the entire range. The useful region is, of course, based on normative data. Regan and coworkers (1981) have shown that on related tasks, individual differences may run as high as 80 to 1, suggesting a wide range of abilities for successful crash-avoidance during low-level flight (see appendix C). These large individual differences may well be responsible for the wide range in Carel's (1961) data previously discussed (figure 3). However, further work is needed to establish the role of size-change mechanisms and to determine whether they are critical for low-level flight.

Evaluating "Optic Flow" The expanding pattern created by forward locomotion includes a plethora of information about the world and one's motion in that world. The problem is to determine how the retinal pattern can be decoded to recover the aspects of the world that are relevant to the tasks at hand. Although some progress has been made in this area (Longuet-Higgins and Prazdny, 1980; Ullman, 1979), still more theoretical and psychophysical work is needed. The brief information analysis in the preceding section suggests that the calculation of the flight angle from the flow pattern would be the next problem to tackle after the derivation of impact time. To solve this problem, the ground plane must be estimated from the retinal flow pattern. Appendix D discusses some aspects of this problem. A study by Harker and Jones (1980) is also relevant. Rather than exploring various parameters of the retinal flow field solely with psychophysics, however, we suggest combining research strategies, as illustrated in this report.

Evaluating Vision Research

The integrated research strategy illustrated above should provide a powerful approach to the fundamental problems of developing more effective visual displays for simulation. This strategy suffers, however, from the "divide and conquer" approach typically used in the laboratory to isolate and study individual processes. This approach fails to

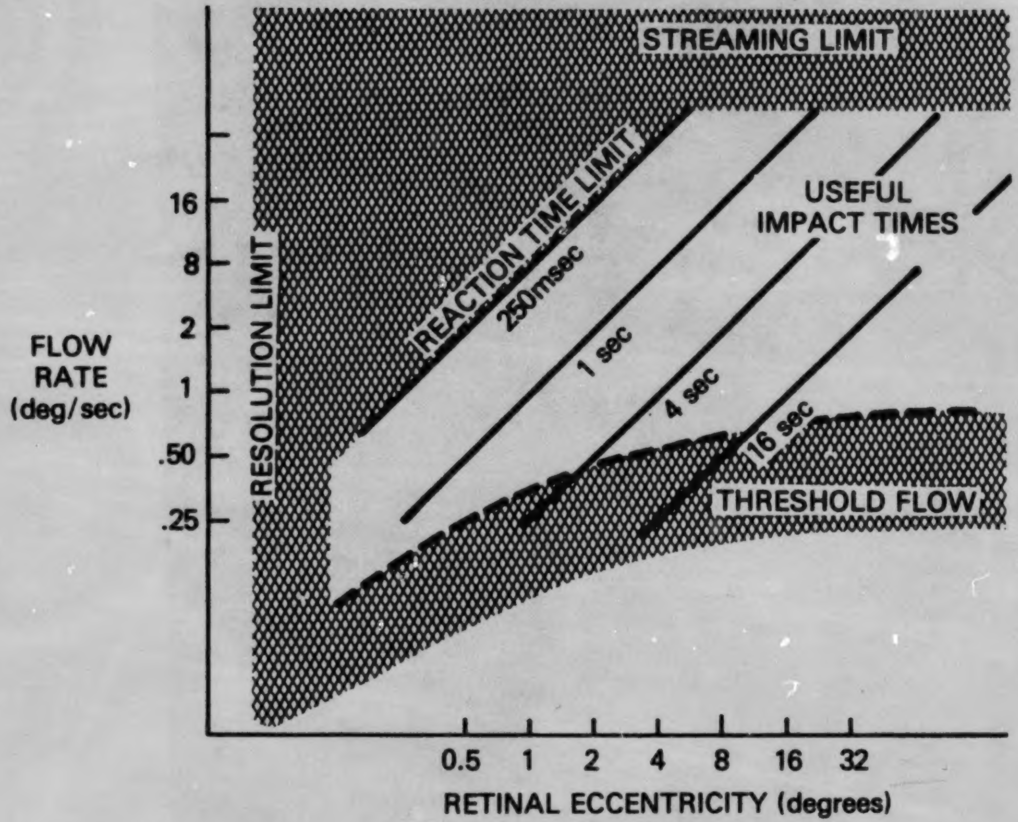


FIGURE 5 Restrictions placed on the useful impact-time loci of figure 2 because of the sensory limitations of the human visual system.

examine visual perception in its natural state, in which visual input is usually rich and redundant. Vision is not merely a collection of independent processes. Sensory information from the eyes is integrated in a complex manner with knowledge of the world and expectations of what will be seen, which are continuously modified as the observer interacts with the environment. Thus, vision is intimately tied to sensorimotor behavior and intellectual problem solving. Studies of the individual processes that derive information from the eyes do not shed light on these interactions. The human ability to use various sources of information and a range of strategies to perform real-world tasks suggests that more than one approach to visual simulation of a given flight task may be effective. It is not possible to determine the most effective approach to visual simulation solely from considerations of vision. All of this indicates that suggestions arising from this or any other research strategy will have to be empirically evaluated to determine their value for simulation flight training.

REFERENCES

Boff, K., and Martin, E.
1980 Aircrew Information Requirements in Simulator Display Design: The Integrated Cueing Requirements Study. 2nd Annual Interservice/Industry Training Equipment Conference, Salt Lake City, Utah.

Brown, J. L.
1976 Visual elements in flight simulation. Aviation, Space and Environmental Medicine 47:913-924.

Carel, W. L.
1961 Visual Factors in the Contact Analog. Reprint No. NR1076(00). Ithaca, N.Y.: General Electric Co.

Caro, P. W.
1977 Some Current Problems in Simulator Design, Testing, and Use. Bolling Air Force Base, Washington, D.C.: Air Force Office of Scientific Research.

Coblitz, D.
1980 Advanced Training Techniques Using Computer Generated Imagery. Annual Technical Report for Period 1 April 1979 - 15 May 1980. Bolling Air Force Base, Washington, D.C.: Air Force Office of Scientific Research.

Fulgham, D. D.
1978 Psychologists vs Engineers. Paper presented at the Royal Aeronautical Society Symposium, "Extending the Scope of Flight Simulation."

Gibson, J. J.
1950 Perception of the Visual World. Boston: Houghton-Mifflin.

Hake, H. W., and Rodivan, A. S.
1966 Perception and Recognition. Ch. 8 in J. B. Sidowski, ed., Experimental Methods and Instrumentation in Psychology. New York: McGraw-Hill.

Harker, G. S., and Jones, P. D.
1980 Depth perception in visual simulation. AFHRL-TR-80-19. Williams Air Force Base, Ariz.: Air Force Human Resources Laboratory. AD-A087 828.

Hennessy, R. T.
1981 Improving simulation training through research. Proceedings of the 1981 Technical Symposium. Washington, D.C.: Radio Technical Commission for Aeronautics.

Hennessy, R. T., Lintern, G., and Collyer, S. C.
1981 Unconventional Visual Displays for Flight Training. Technical Report NAVTRAEQUIPCEN 78-C-0060-5. Orlando, Fla.: Naval Training Equipment Center.

Hennessy, R. T., Sullivan, D. J., and Cooles, H. D.
1980 Critical Research Issues and Visual System Requirements for a V/STOL Training Research Simulator. Technical Report NAVTRAEQUIPCEN 78-C-0076-1. Orlando, Fla.: Naval Training Equipment Center.

Kelly, D. H.
1979 Motion and vision II. Stabilized spatial-temporal threshold surface. Journal of the Optical Society of America 69: 1340-1349.

Kraft, C., Anderson, C. D., and Elworth, C. L.
1980 Psychophysical criteria for visual simulation systems. AFHRL-TR-79-30. Williams Air Force Base, Ariz.: Air Force Human Resources Laboratory. AD-A084 776.

Kruskal, J. B., and Shepard, R. N.
1974 A non-metric variety of linear factor analysis. Psychometrika 39:123-157.

Langewiesche, W.
1944 Stick and Rudder. New York: McGraw-Hill.

Llewellyn, K. R.
1971 Visual guidance of locomotion. Journal of Experimental Psychology 91:245-261.

Longuet-Higgins, Ch., and Prazdny, K.
1980 The interpretation of a moving retinal image. Proceedings of the Royal Society of London Series B. 208(1173):385-397.

Orlansky, J., and String, J.
1977 *Cost-Effectiveness of Flight Simulators for Military Training*. Arlington, Va.: Institute for Defense Analyses.

Regan, D. M., and Beverley, K. I.
1979 Binocular and monocular stimuli for motion in depth. *Vision Research* 19:1331-1342.

1980 Visual responses to changing size and to sideways motion for different directions of motion in depth. *Journal of the Optical Society of America* 70:1289-1996.

Regan, D. M., Kruk, R., Beverley, K. I., and Longridge, T. M.
1981 The relevance of channel theory on the design of simulator imagery. Pp. 307-344 in the unpublished proceedings of the Image Generation/Display Conference II, conducted by the Air Force Human Resources Laboratory, Williams Air Force Base, Ariz.

Richards, W.
1980 Quantifying sensory channels (generalized colorimitry). *Sensory Processes* 3:207-229.

Semple, C. A., Hennessy, R. T., Sanders, M. S., Cross, B. K., Beith, B. H., and McCauley, M. E.
1980 *Aircrew Training Device Fidelity Features*. AFHRL-TR-80-36. Wright-Patterson Air Force Base, Ohio. Advanced Systems Division, Air Force Human Resources Laboratory. AD-A094 665.

Simon, C. W., and Roscoe, S. N.
1981 *Application of a Multifactor Approach to Transfer of Training Research*. Technical Report NAVTRAEQUIPCEN 78-C-0060-6. Orlando, Fla.: Naval Training Equipment Center.

Ullman, S.
1979 *The Interpretation of Visual Motion*. Cambridge, Mass.: MIT Press.

Waag, W. L.
1981 *Training Effectiveness of Visual and Motion Simulation*. AFHRL-TR-79-72. Williams Air Force Base, Ariz.: Air Force Human Resources Laboratory. AD-A094 530.

Westra, D. P., Simon, C. W., Collyer, S. C., Chambers, W. S., and Nelson, B.
1981 Investigation of simulation design features for the carrier landing task. Technical Report NAVTRAEQUIPCEN 78-C-0060-7. Orlando, Fla.: Naval Training Equipment Center.

Wilson, H. R., and Giese, S. C.
1977 Threshold visibility of frequency gradient patterns. *Vision Research* 17:1177-1190.

APPENDIX A

ANALYSIS OF NON-METRIC DATA

D. H. Fender

It seems almost a truism that pilots must know a great deal about those aspects of the visual environment that contribute to the successful performance of their task. Simulation researchers, however, report that the subjective assessments of pilots are not a reliable guide to the visual information actually used in flying.

My evaluation of the problem is that pilots are probably not consciously aware of what they know about this problem, cannot turn this knowledge into reliable verbal forms, and that the information is probably non-metric anyway. I persist in my belief that there must be a mine of information residing with pilots; the major problem is to devise reliable ways of tapping and analyzing this information.

There are two problems here--how to tap the information and how to analyze it. Let me deal with the second problem first. Since the data are most likely non-metric, the analytic method of my choice would be multidimensional scaling with an unknown proximity function, as suggested by Shepard (1962). This analytic method requires that we have a confusion matrix (or proximity matrix) between the nonparametric properties of the simulator visual environment that we wish to study, and this dictates the form of experiment that we should do to tap the pilot's experience.

For example, if we wish to analyze the present simulator we might start by asking the subjects to write down a list of all the attributes they can think of that apply to the visual environment of the simulator. We would probably get a pretty conventional list, such as

(a) field of view
(b) monochromatic display
(c) collimated viewing condition
(d) resolution of the display
(e) representation of landscape
(f) movement of display contingent on maneuvers of plane,

and a few unusual items, such as

(g) fingerprints on cockpit canopy
(h) flicker in peripheral vision

Some might even object to the projective geometry used in the display, and record

(i) Euclidean geometry!

and so on.

We would then take the combined lists of all of the subjects, possibly add a few attributes of our own, and then put the following problem to the subjects:

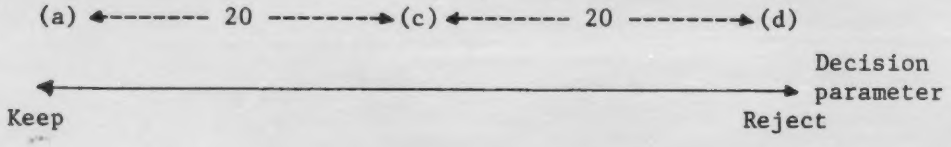
> In the design of a future simulator we shall not be able to incorporate all the attributes of the one with which you are familiar. You will therefore be asked to select between pairs of attributes. Your task is to say which of the pair you would retain in the new design. We make the assumption that the attribute you do not select will be (i) eliminated (as in the case of platform motion), (ii) degraded so as to be useless in the performance of the task (as in the case of resolution) or (iii) changed so that the effect on you becomes objectionable (as in the case of peripheral flicker). In short, a vote against an attribute is always to be interpreted as "change the attribute so as to degrade the performance of the flying task." Thus a vote against fingerprints does not mean "remove them," it means "make them worse." Some pairs may seem to represent an impossible choice, for example, contrast versus resolution, since complete degradation of either will kill the visual input; but please make a choice anyway!

After the experiment has been performed, using for example a population of twenty, we would have a matrix such as follows, where the number in each cell represents the number of subjects voting for that condition:

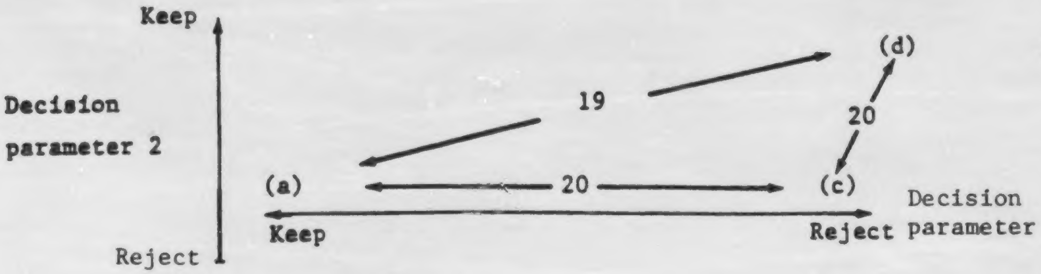
Attribute Rejected

Attribute Retained	a	b	c	d	e	f	g	h	i	j	. . .
a	■	15	20	1	3	5	10	13	2		
b	5	■	4	15	8	11	11	14			
c	0	16	■	20	19	4	13				
d	19	5	0	■	5	7					
e	17	12	1	15	■	10					
f	15	9	16	13	10	■					
g	10	9	7								
h	7	6									
i	18										
j											
. . .											

A consideration of these numbers alone begins to give some idea of how the subjects perceive the flying task; for example, twenty voted to exclude (c) in relation to (a), but equally twenty voted to include (c) when compared with (d). Already we begin to see the relative merits of (a), (c), and (d) insofar as the subjects are concerned; we could possibly lay them out along a decision axis, such as that shown below:



But this is patently wrong when we consider (d) against (a)--nineteen voted to keep (d) and reject (a)! It is probable that the (a,d) decision was made on a different parameter from that used in the (a,c) decision or the (c,d) decision. In this case a better layout might be as follows:



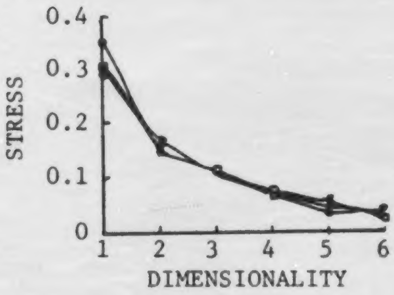
Obviously, the geometry doesn't quite work out, but it might be possible to juggle the layout so that at least the rank ordering of the interpoint distances is monotonically related to the experimental data. We might be able to do this in our heads for a small number of data points, but the complexity increases rapidly with the number of points.

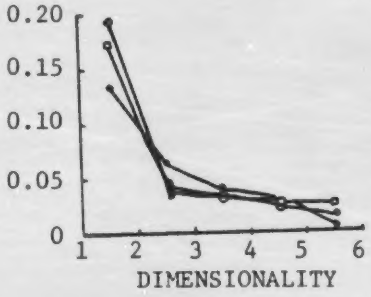
For a group of N points, any prescribed rank order of the N(N-1)/2 interpoint distances (including ties) is realizable in an Euclidean metric space provided it is of dimension N-1 or greater. Suppose that we had tested nineteen attributes; this means we could display the 171 proximity measures as metric distances among nineteen points in an 18-dimensional space. Apart from the obvious problem of visualizing an 18-dimensional space, such a configuration would yield little more information than the simple rank ordering of the 171 proximities. It is therefore highly desirable to reduce the order of our metric space if we can do so without distorting the representation of our proximity measures.

The mechanism for reduction of dimensionality proposed by Kruskal (1964) is based on finding a structure that maintains the monotonicity condition. For a given configuration in a space of dimension n, where $n \leq N=1$, a monotone regression of distance upon proximity measure is performed and the residual variance used as a measure of how well the particular configuration satisfies the monotonicity condition. This measure Kruskal calls the stress. The configuration is changed iteratively following a nonlinear minimization algorithm based on the method of steepest descent until the configuration with the smallest possible stress is obtained for that order space. Hence, the dimensionality of the space may be reduced so long as a configuration can be found that yields a value of stress that is acceptably small. If this condition is satisfied, then the structure in the lower-order space is just as valid a representation of the proximities as the 18-dimensional structure. A large stress value implies monotonicity is not maintained and hence the configuration does not very well represent the psychophysical data.

It is of considerable interest to determine the minimum dimensionality space in which a configuration can be found that adequately represents the psychological proximities. The number of dimensions required can then be associated with the number of fundamental properties of the stimuli upon which the discriminations are based. But it is also important to remember that this scaling technique is only a conceptual convenience; visualization of a configuration in a low-order space is facilitated and can reveal important aspects of the interpoint relations.

I have used multidimensional scaling in a number of contexts, and my experience has been that the human can make decisions only in a space of very low dimensionality. Typically, the curves of stress versus dimensionality in an experiment designed to differentiate between visual textures (Santoro and Fender, 1976) look thus:

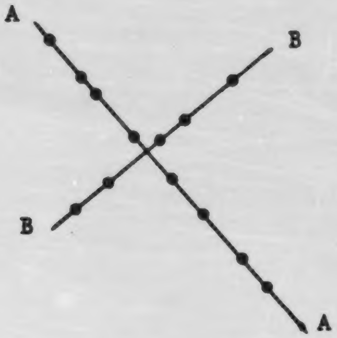




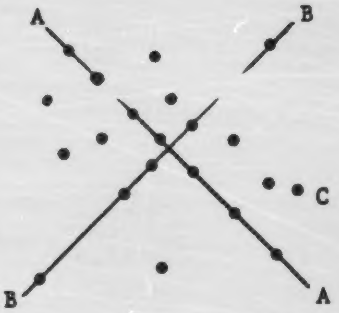
●= subject 1. ○= subject 2. □= subject 3.

Curves such as these indicate that a 3-dimensional configuration would probably describe the data adequately, and a model of higher dimensionality would overfit the data.

It is at this point that the wit of the experimenter enters the problem. The computer merely churns out a mass of numbers; the nineteen attributes are positioned in n-space so as to minimize the stress, where n is chosen by the experimenter from a curve such as the one above. The computer gives the coordinates of the points representing the attributes. For simplicity of visualization, let us assume that we can represent the data in 3-space. We next perform a varimax rotation, that is, we find the axis such that if the data points were projected onto a plane perpendicular to this axis, the variance of the data would be reduced by the maximum amount. The two other orthogonal axes satisfying the same condition are also calculated. We then have to think. Suppose that the data were as follows (reduced to 2-space for further ease of visualization):



That is, the data points lie very neatly along the varimax axes AA and BB. We obviously have two intermingled classes of data, one differentiated by whatever property is mapped along AA and the other by the property mapped along BB. The experimenter then has to examine the attributes that are mapped along AA; only his insight will help him understand what property lies along AA and is scaled such that the attributes at one end (the analysis doesn't tell you which end!) have "a lot" of this property while those at the other end have "not very much" of the same property. The same process can be performed along BB. The analytical thought process becomes more complex if the data points are as shown:



That is, there are many points such as C that do not lie on AA or BB. The point C can have any lot/little combination of the properties AA and BB, since we do not know a priori which way the properties are scaled along the axes. In general, one uses the points lying on axis to develop ideas about the property mapped along each axis, and then one checks the off-axis points against these theories. Of course, it may happen that no points in the data structure lie on axis!

The outcome of this analysis--which is not exact by any means--is a strong indication of the parameters the subjects used when making their decisions to accept or reject an attribute. Whether these decisions have any link with flying a simulator depends on the skill with which the original experiment was set up. But suppose that the work is well done; the design principle is then self-evident--add (or enhance) features whose attributes lie at the "good" end of the longest axis, and if compromises have to be made, lop off features whose attributes lie at the "bad" end of any axis.

The most evident criticism of this approach is that if an attribute is not included in the original list, it will not appear in the final analysis. This is a potent criticism but fortunately not a fatal one--the analysis proceeds perfectly well without the missing attribute, and in many cases an examination of the axes of the final structure prompts the experimenter in regard to attributes that may have been missed. The work can then be repeated in an iterative fashion.

The experiment described earlier is put forward only as an example of how multidimensional scaling might be applied. Many other experimental arrangements are possible, and workers more closely in touch with the simulator problem are surely the ones to design the actual experiment. For example, rather than giving a colloquial explanation of what a vote against a particular attribute might mean, it may be better to seat the subject in the simulator and say, "If you vote against resolution, this is what will happen," then tweak the knob to blur the image, and so on over all the attributes, before the subject is asked to cast his vote.

Further, instead of adjudicating between attributes in a simulator, the subject might be asked to evaluate an attribute in the simulator against the same attribute in a real plane, or in another model of simulator, on a scale of one to five, for example.

A program to perform this analysis is available commercially. It has many features not treated here. They are described in Kruskal et al. (1973). One feature, however, is worth mentioning. The program has the ability to analyze data represented by two or more proximity matrices simultaneously. That is, it derives the structure that is the best fit to both matrices. One way to exploit this would be as follows: If any objective data exist on the merits, or relative merits, of any of the attributes, these could be plugged into a second matrix. It is not necessary to fill all the cells of the matrix. The program works quite well on an incomplete matrix. If the analysis is then run on the two matrices, using varying weighting factors between them, at the least, it is possible to test the concordance of the subjective and of the objective data.

In summary, I propose that the method of multidimensional scaling provides a technique that could be applied rapidly and at low cost to the backlog of objective information concerning flight simulators and to subjective information that could be gathered without too much experimental effort. At worst, the analysis might tell us no more than we already know, but at best it might give considerable insight into the functional attributes of a flight simulator and of the interactions between them.

Other aspects of multidimensional scaling are explored in Shepard (1974), Shepard et al. (1972), Kruskal and Shepard (1974), and Egan (1971).

REFERENCES

Egan, D. M.
1971 Executive performance appraisal: An application of nonmetric multidimensional scaling. Proceedings of the Academy of Management. Oregon State University. Corvallis, Ore.: 49:75-80.

Kruskal, J.
1964 Multidimensional scaling by optimizing goodness of fit to a non-metric hypothesis. Psychometrika 29(1):1-27.

Kruskal, J., and Shepard, R. N.
1974 A nonmetric variety of linear factor analysis. Psychometrika 39:123-157.

Kruskal, J., Young, F., and Seery, J.
1973 How to use KYST, a very flexible program to do multidimensional scaling and unfolding. Document 1-50. Murray Hill, N.J.: Bell Laboratories.

Santoro, T. P., and Fender, D. H.
1976 Rules for the perception of connectivity in random dot patterns. Vision Research 16:973-981.

Shepard, R. N.
1962 The analysis of proximities: Multidimensional scaling with an unknown distance function I. Psychometrika 27(2):125-141.

1974 Representation of structure in similarity data: Problems and prospects. Psychometrika 39:373-421.

Shepard, R. N., Romney, A., Kimball, N., and Nerlove, S. B.
1972 Multidimensional Scaling: Theory and Applications in the Behavioral Sciences: I. Theory. New York: Seminar Press.

APPENDIX B

COMPUTATIONAL ANALYSIS: IMPLICATIONS FOR VISUAL SIMULATIONS OF TERRAIN[1]

Kent A. Stevens

Introduction

Low-level flight (LLF) is a flight regime of increasing importance in combat and also a regime where significant difficulty has been experienced in its simulation. Pilots who are expert in actual LLF often cannot duplicate their performance in the simulator. When "on the deck" in the simulator they have difficulty both in following the contour of the terrain at low altitude (without crashing) and in judging altitude. In part, the difficulty is technological; for instance, the very rapid motion of terrain detail across the display requires fast display processors. Other difficulties are perceptual: the visual displays must convey an adequate 3-D understanding of the terrain over which the pilot must fly. The combination of technological and perceptual problems has prompted some reexamination of the methods for terrain depiction. This paper describes a new technique that may improve the visual simulation of terrain, as applied to the simulation of LLF.

The introduction will discuss three background issues. The first concerns flight training. Research and development efforts regarding simulators for flight training should be evaluated in terms of their impact on training. However, LLF simulation presents some basic visual problems that must be solved regardless of whether the simulator is used for training or any other purpose. Hence we concentrate here solely on the visual problems of LLF simulation. Next, we show that although real world scenes are distorted in computer image generation (CIG) displays, they can still convey useful 3-D information. With that observation we turn to problems of defining "information content." Finally, we discuss a computational methodology for studying human vision that approaches complex systems at several levels of detail or specificity, where different theoretical tools are appropriate at each level. This approach has led to succinct and precise descriptions of various processes of human vision (such as stereopsis and edge detection, see later). That point is crucial for its application to flight simulation; even though we currently have only a limited understanding of the overall visual system, many facts that we do know translate into important suggestions for simulator scene generation. The rest of the paper attempts to show how that insight comes about.

---

[1] This is a revision of the paper that appeared in the Image Generation/Display Conference II in June 1981. A number of people made important contributions and suggestions: Prof. W. Richards and Drs. S. Collyer, D. Regan, J. Richter, and S. Ullman. The author gratefully acknowledges the useful comments on an earlier draft of this article provided by Drs. K. Dismukes, R. Haber, and J. Hochberg. The manuscript was prepared at the Artificial Intelligence Laboratory of the Massachusetts Institute of Technology, with support provided in part by the Advanced Research Projects Agency of the Department of Defense under Office of Naval Research contract N00014-75-C-0643 and in part by the Air Force Office of Scientific Research and the National Science Foundation under MCS79-23110.

Some Remarks Regarding Training

The flight simulator that we have in mind is a device for training low-level flight. One school of thought is that a training device should be optimized for the particular training task for which it is intended. Consequently, the distinction between training a skill to a novice and training for performance or skill maintenance should be reflected by the simulator system, for example. But it is doubtful the state of the art of LLF simulation is sufficiently advanced as to make this distinction worthwhile as of yet. There are clearly two rather diverse types of research required: applied visual science in order to improve the effectiveness of the visual display, and training research in order to optimize the effectiveness of the overall system for flying training. Both types of research are needed; the question is to what extent they might profitably be undertaken independently. One might argue that if one attends solely to the visual problems (without regard for its role as a device for training pilots), one might inadvertently concentrate on visual problems that are unimportant to training, or overlook problems that are important to training. That danger exists, but the problems that beset LLF simulation are probably intractable unless some decomposition is made of the overall complex of issues.

The pragmatic view taken here is that careful research into the generation of visual scenes (that leads to greater precision in interacting with the environment) can proceed without much regard for the larger role of the display in training. But also, careful research is needed regarding the training proper. For example, if one is to pursue optimization of the simulator for a particular type of training (novices versus skill maintenance, say), it is necessary to understand how the two training tasks differ and how the visual displays should reflect those differences, in principle. But these issues are also difficult. For example, even in the case of simulated landings (probably the best-studied flight maneuver for simulation), it is neither intuitive nor (to my knowledge) empirically known how to optimize the visual display for maintenance versus undergraduate training. Thus there are two issues at hand: visual perception and optimal pilot training. Effort on one problem should not be made at the exclusion of the other. However, we will not deal with issues of training here.

Differences Between CIG Simulation and Real Terrain

When the CIG simulation of LLF is compared to the real world seen from a low-flying aircraft, the simulation seems oversimplified and somewhat corrupted by artifacts, such as the stuttering effect that results when the CIG system cannot update the display in the periphery often enough given the large angular velocities associated with LLF. One might conclude that the 3-D impression would be adequate if only one had greater display capability. But it is conceivable that even a hundredfold improvement would not solve the problem.

Insufficiency of detail is not the whole story. A simulation scene is not merely a simplification of a real scene; there are dramatic and qualitative differences. In reducing the bandwidth of a real visual scene to manageable proportions, there is no straightforward sampling technique available--we cannot merely take every n-th bit of information, as it were. Instead, we construct a novel and unique world out of relatively few edges and perhaps shading, color, points, and lines.

The visual world we construct in the simulator shares many similarities with the real world. The single most important similarity is that the rules of perspective geometry are preserved in the simulation. That means the visual world in the simulation behaves optically as we expect. This point should not be underrated, for it is responsible for much of the success of visual simulation.[2] Specifically, the perspective transformation by which the simulator CIG system projects 3-D points, lines, and surfaces from the terrain model onto the 2-D display screen (and in turn, onto the retina so long as the display is viewed from the proper location) precisely corresponds to the way real 3-D points project onto the retina.[3] Consequently, any static view is reproduced with geometric precision (e.g., the proper "texture gradient" is generated because increasingly distant surface elements appear progressively smaller). Also, if the surfaces are modeled as opaque, the CIG system (usually) has the capability to make nearer surfaces occlude from view those that are farther. Moreover, if we move in space, the continuous changes in perspective of points and surfaces also correspond geometrically to what happens in the real world. Consequently, we also have geometrically correct "optic flow," "motion parallax," and so forth (see later). It is the fact that perspective projection is accurately duplicated by the CIG system that was responsible for the compelling effect of space in early night-flight simulators, where only moving luminous dots (such as runway lights and city lights) were projected. As opaque surface shading was added and daytime scenes were simulated, the additional gains came, in part, from the visually apparent occlusion of distant objects by nearer ones. But along with attempts to simulate daytime scenes came the realization that the simulation is very different from the real thing.

---

[2] Here we are suggesting that much of the three-dimensionality comes by having correct perspective, regardless of what is displayed in perspective. But that is not to say that some benefits cannot be achieved by carefully crafted distortions to the perspective (see Finch, 1977).

[3] But see Kraft et al. (1980) for engineering considerations.

One difference of probably minor importance is that the display is effectively a monocular presentation (see later). But just to note a few of the profound differences between the real scene and the simulated counterpart, observe that real surfaces have detail at all scales, and that new detail is continuously revealed as one approaches a surface. But the limited detail that most CIG systems can display combined with their resolution limits result in drastically simplified scenes. (This fact may be particularly relevant to the LLF question, as pilots in real flight conceivably use fine recognizable detail of vegetation and rocks in order to judge their distance from approaching terrain.) Another difference is that real surfaces are not restricted in their 3-D shape (consider a rolling desert floor or an eroded canyon wall). But the usual computer representation of curved surfaces in terms of planes bounded by polygons results in a dramatically different sort of terrain than would be found in nature. As it is not simply the fact that the surface is piecewise planar rather than continuously curved, it is also not true that sharp straight boundaries occur at every junction. Those straight boundaries are also used to denote field boundaries (such as the checkerboards which resemble agricultural land). In fact, the basic element in simulation for representing surfaces is an edge across which screen intensity is sharply discontinuous. The intensity edge may represent a sharp physical feature such as a cliff, ridge, or corner of a building or a place where the surface reflectance sharply changes, such as the border of a runway or the edge of a checkerboard square. Some display systems have shading and modulation of contrast to approximate atmospheric haze or fog, but generally the intensity edges are equally sharp and homogeneous in CIG simulations, and that is not natural. Another point is that actual surfaces have physical texture in relief above the mean surface level (bushes above the ground, peaks and troughs of waves) but this is costly to generate in current simulator systems. One final difference should be pointed out: actual surfaces reflect light in a complex way depending upon the orientation of the light source (the sun and the overall sky illumination), the orientation of the viewer relative to the surface, and the physical properties of the surface. But generally the intensities of simulated surfaces are unnaturally constant and homogeneous--even the most sophisticated techniques for shading surfaces are highly simplified.

This discussion is not intended to point out the well-appreciated fact that CIG scenes are unrealistic. Its purpose is to show that simulated terrain is an extreme and stylized simplification of the real world. That is not necessarily detrimental, however, for human vision has a remarkable ability to ignore simplifications in illustrations. For instance, we are all familiar with the strong visual impact that even simple line drawings provide, such as seen in engineering and mathematics texts and in assembly instructions. While they are highly unrealistic, we seldom attend to that fact. Since they carry the necessary 3-D information, they serve their purpose; it does not matter that actual surfaces give rise to more complicated images. Similarly, it may be argued that simulation displays of terrain may be adequate (for purposes of training, etc.) and yet highly unrealistic and caricatured.

Problems with Intuitive and Geometric Argument

Thus we have that the CIG display may carry the necessary 3-D information despite the unrealistic qualities just described. But we still have to formalize what we mean by "necessary 3-D information." In that pursuit it should be stressed that our intuition should not be trusted. Intuition is often wrong regarding the way the human visual system operates. In short, what we naively believe to govern our visual perceptions is often not the case. It is worthwhile examining one such example in detail. The example involves the familiar (static) texture gradient, specifically, that the texture density seems intuitively to be the crucial depth cue in texture gradients the higher the density, the greater the distance to the surface (Gibson, 1950); see also the geometric analysis in Purdy (1960). In fact, distance cannot be inferred directly from density (the following argument is summarized from Stevens [1980]). The reason is that texture density is a function not only of the distance to the surface but also of the slant of the surface relative to the viewer (the greater the slant, the greater the foreshortening and hence the greater the texture density). In the case of an arbitrary surface, one cannot decouple the relative contributions to the density gradient caused by foreshortening from that due to distance. Consequently, one cannot infer distance from texture density. This argument provides an explanation for the largely ignored psychophysical evidence (e.g., Smith and Smith, 1957; Braunstein, 1968; Braunstein and Payne, 1969) that texture density is an ineffective cue to distance. This result is contrary to our intuitions. It points out that we must go beyond introspection.

In the same vein, it is not sufficient merely to examine the geometric properties of perspective projection. For instance, the analysis of texture gradients that Purdy (1960) performed set out to find a geometric basis for the hypotheses that Gibson (1950) set forth (such as the one just discussed). But such geometric analyses must be carefully regarded, as they implicitly embody certain geometric assumptions, such as that the ground is globally planar (see Purdy, 1960). The mathematical relations derived with those assumptions, of course, do not hold when the physical surfaces are not so constrained (e.g., when the textured surface is not planar). It is not a straightforward matter to set down the geometric relations that provide the basis for visual interpretation of the image. The relations necessarily incorporate constraints, and it is a separate and nontrivial matter to verify that those constraints are adopted by the actual perceptual processes of human vision. For further discussion on the matter of constraints and its relation to Gibson's "direct perception" hypothesis, see Ullman (1980).

How Is Information Encoded in the Image?

Image information content is usually discussed in terms of depth cues such as texture gradients, optic flow, and stereopsis. But to be useful, in particular to be useful for flight simulation, those terms must be defined more precisely than is usual in the psychological literature (see also Hennessy et al., 1980; Semple et al., 1980). To illustrate, consider the difficulty a simulator designer would have trying to apply a general fact about optic flow. For argument, suppose he reads that optic flow provides information about the direction of travel because of the streaming of detail radially away from the point he is approaching (Gibson, 1950). If the designer learns that pilots often lose visual orientation in the simulator (while maneuvering, say), the designer would recall that optic flow is relevant. But the designer is now stuck, in a word, because optic flow was not defined with sufficient specificity that the designer might translate that suggestion into an improved visual display. It is a rather subtle point that optic flow is inevitable whenever one moves through other than empty space. Optic flow is a consequence of perspective projection and motion, so regardless of how the terrain is depicted, if one moves across it, the resulting movement of detail across the visual field is optic flow.

The designer is faced with a terrain simulation that is apparently inadequate, seeks to improve it, and knows that optic flow is relevant. So he considers the variables that govern optic flow, those being the parameters of motion relative to the surface as well as the qualities of the surface texture itself. (The faster and lower the aircraft, the more pronounced the apparent optic flow; also, the more densely textured the surface, the greater the effect.) Of these variables, it is only the surface texture that the designer may manipulate, but how to do so? Insight would come from knowing something about how the human visual system measures and internally encodes moving texture and how it extracts 3-D information such as orientation from those measurements. We cannot dismiss this issue in a cavalier manner, trusting that the human visual system will extract what it needs so long as the CIG display is rich enough in detail. Current (and foreseeable) CIG display technology does not (and probably will not) have the capability of reproducing the complex visual texture presented by real LLF over natural terrain. Rather, we should devise more efficient uses of the CIG system's ability to generate texture. We might think of this as "impedance matching," of matching the type of texture that is displayed with the type of visual processing we make on that texture, so as to optimize the information transfer. For instance, the visual display might concentrate its detail at the (instantaneous) point of gaze and capitalize on the fact that visual resolution degrades with eccentricity.[4] But much more thought is needed; it is not enough to discuss what might be omitted (such as detail in the periphery) but what might be included in the texture. Such thought requires that one examine the visual processes in terms more analytical than simply "depth cues."

A Computational Information Processing Approach

We now sketch an approach to the study of vision which has application to visual simulation. It is probably well to remark at the outset that this approach stands among many approaches to vision research. Later we will see how this approach, because of its different perspective, emphasizes certain issues of terrain depiction that have not been addressed previously in simulation research.

It has long been regarded that vision embodies processes that derive information about the visual world from the interpretation of retinal images. To be sure, virtually every phrase in the previous statement has been contested, cast in a different light, or relatively emphasized by a particular theoretical viewpoint. For instance, Gibson (1950, 1979) characterizes human vision as direct registration of higher-order variables in the visual stimuli, thereby downplaying the need for interpretation and information processing (but see Ullman, 1979). There are some conflicting theories of visual processing, but largely the differences are of emphasis. For instance, some researchers concentrate on the fact that our perception is often as much a product of what we expect as what is objectively present in the image. Others concentrate on the fact that natural scenes have richly redundant and consistent sources of information, and argue that since human vision probably capitalizes on that fact, experiments using simplified stimuli must be carefully interpreted.

Another theoretical viewpoint is exemplified by the computational approach of Marr (1976, 1978, 1981) and Marr and Poggio (1977), which examines the information processing aspects of vision. The value of this approach to vision research stems largely from recognizing (i) that human vision involves complex information processing, and (ii) that complex systems are feasibly understood by us only when described at several levels of detail and abstraction. The first point is well accepted by psychologists (in fact, some researchers find the complexity overwhelming and believe we will never understand the processes of vision because of their complexity). The second point is well accepted by engineers, and particularly computer scientists, who see the need for making clean distinctions between the purposes or goals of a complex device, the methods by which it achieves those goals, and the particular nuts-and-bolts details of how they are carried out. The vocabulary used for describing what a system accomplishes is very different than that used for describing how it does that (at various levels of detail, culminating in the physics of transistors, or whatever comprises the basic building blocks of the system). Complex information processing systems require this sort of multilevel description; any one level of description, alone, would be inadequate. For instance, the circuit diagram of a digital computer at the level of individual transistors and capacitors would be incomprehensible, if it were not for additional descriptions of how the electronic components implement logical functions such as "and" and "or," and how those functions are sequenced to achieve processes, and so forth. Marr argues that biological information processing should be similarly approached. Neurophysiology and anatomy provide us some understanding of the detailed architecture of the visual system, but just as studying the physics of a transistor reveals nothing about operating systems or Fortran compilers, neither does study of neural synapses reveal the principles of stereopsis or motion perception.

---

[4] One should be careful here, because while resolution degrades with eccentricity, temporal processing is still strong (e.g., flicker and motion are readily detected in the periphery).

This computational approach describes visual processes at several levels.[5] Ideally, one would like to understand some visual process (such as stereopsis) at all levels, from the abstract and mathematical down to the level of neural implementation. But it is only for certain very early stages of visual processing (such as retinal function) that neurophysiological details are feasibly incorporated into a computational theory as of yet (see Marr and Hildreth, 1980; Richter and Ullman, 1980). Of course, one can have a significant and useful understanding of a complex mechanism without knowing its implementation details. By and large, the theories emerge "top-down," with the initial insights gained at the level of what the visual system computes (regarding, for instance, stereopsis) and the theoretical basis for that computation. This sort of research is reminiscent of Gibson and his followers, for one is concerned with geometric constraints and feasibility. But, in contrast, the computational approach concerns itself with the form in which visual information is encoded or made explicit within the visual system. The 3-D representations are described abstractly, not at the neural level (that sort of understanding is far from us at the present) (Marr, 1976, 1978; Marr and Nishihara, 1978; Stevens, 1980).

In formalizing the computations that underlie vision, one makes rigorous the form in which the visual information is made explicit by the visual system, the sources of that information in the image, how that information is actually extracted and measured, and finally the computational constraints necessary to interpret that information. This sort of vision research has relevance to simulation, therefore, because understanding how information is extracted tells us how it should be presented. Also, the constraints that visual processes incorporate are essentially perceptual assumptions about the nature of the visual world. Those assumptions are either always valid, because of the physics of solid objects, perspective, and optics, or the assumptions are usually valid because of the statistical properties of the world; see Ullman (1979) for discussion of assumptions in computational terms and Gibson (1979) for the related notion of "ecological optics." These assumptions have relevance to simulation, for in laying out a simulated 3-D environment it is important to have its properties match our visual assumptions; otherwise, our perceptual reconstruction of that environment will not correspond to what was intended. A specific example will be given concerning the assumptions underlying our interpretation of surface contours. Those results are primarily geometric; other relevant contributions to simulator research pertain to efficient depictions of texture.

---

[5] See Marr and Hildreth (1980) and Richter and Ullman (1980) for detailed theories of retinal processing and edge detection. See Marr and Poggio (1979), Mayhew and Frisby (1981), and Grimson (1980) for computational theories of stereopsis. See Ullman (1979) for visual motion, and Stevens (1980, 1981) for texture gradients and surface contours.

The rest of the paper reflects on the problems of depicting terrain for flight simulation from the computational perspective.

Shape, Orientation, and Scale

Let us consider in general terms what the pilot's visual system must accomplish in order that an aircraft may be maneuvered at low altitude over actual terrain. Of course, the shape of the terrain must be perceived in 3-D, so that a close earth-hugging course might be followed. But not merely the shape must be known, but also its size or scale. A small hill and a mountain might have the same shape but differ significantly in scale. We will need to become more specific about shape and scale, but let us continue informally for a moment. One must also know the pilot's orientation and altitude relative to the terrain. The pilot, it is reported, envisions himself as following a path through space above the ground, where he keeps a mental trace of where he has been, where he is, and a projection in front of him of where he is going. In large part this must come from his visually perceiving his orientation relative to the terrain. We must also be specific about what this entails.

We have singled out shape, scale, and orientation as three classes of visual information necessary for flying over terrain. Although we are being informal in our use of the terms, these three notions seem amenable to a precise definition eventually. But is this decomposition of the visual requirements for LLF into the perception of shape, scale, and orientation the best decomposition for purposes of improving the visual simulation? It certainly seems that each form of information is basic and necessary. On the other hand, concern is perhaps warranted that the shape, scale, and orientation are not sufficiently inclusive; we might be omitting some different quality of 3-D information which is necessary for LLF. (Note that we are not considering information about tactical targets, navigation cues, and so forth. Rather, we are solely concerned with the information that must be gathered by the visual system so that the pilot might fly just above the terrain.) We do not know the answer to that question; nonetheless, the shape-orientation-scale approach to describing necessary information should prove useful even if it is not the "whole story."

The distinction between shape and scale is important. Human vision is often surprisingly imprecise about scale: we appreciate the shape of a microorganism from a scanning electron micrograph without any concern for (or appreciation of) its size; likewise, an astrophotograph of a nebulus imparts in us no sense of scale. This phenomenon is not difficult to explain theoretically; it is likely that the internal representations of visual shape are inherently scale-independent (see the notion of scales in Haber and Hershenson (1980) and the representations of surface orientation in Attneave (1972) and Marr (1978). Furthermore, the visual system probably treats as distinct perceptual problems the determination of an object's shape and size. This distinction between shape and scale is often nonintuitive because in everyday scenes we usually have rich sources to both forms of information; there are many convergent perceptual processes that provide information about shape, and there are many means by which we directly and indirectly determine the actual size and distance of visible objects. The scale of our immediate surrounding area is usually so precisely known that we interact in it with grace and facility. But we are also faced with natural situations in which the scale information is relatively impoverished. One case with which most of us are familiar concerns viewing the earth from the air, where the shape of the mountains or canyons is clear to us, but their size is appreciated only if, say, we detect a cabin, or a car on a road. We then experience a sudden and sometimes shocking appreciation of the scale of the scene and, simultaneously, of the actual distances involved. (The apparent shape remains unchanged; however, after we learn the scale, it is as if independent information is added to our perception.) The crucial points we should draw are two: (i) scale and shape are distinct forms of information about the 3-D world, and (ii) both forms of information are needed in order to interact precisely with the world.

The third class of 3-D information, orientation, has many facets and is closely intertwined with shape. First we will discuss what we mean by orientation and then show how shape and orientation relate. Gibson (1950) discusses two qualities of orientation; one local, the other global. The local orientation of surfaces is defined relative to the viewer; one's orientation in space is defined globally relative to the surrounding visual environment. Let us consider each in turn. It is natural to visualize the orientation of a patch of surface relative to oneself. The slant angle between the line of sight and the normal to the surface is one way of quantifying this. When viewing a large planar surface such as the ground seen from the air, there is a wide range of relative surface orientation (zero slant directly below the aircraft, slant approaching 90 degrees toward the horizon). But we think of the planar surface as having one orientation, not merely a local orientation that depends on which patch of the surface we view. If the plane rolls, we see the orientation of the ground change relative to us. We clearly have the ability to judge orientation more globally, e.g., relative to the horizon.

We have discussed two sorts of orientation information: information about the attitude of individual patches of surfaces relative to the viewer, and the overall orientation of a large surface such as the ground seen from the air. There is another related sort of information which also seems primitive and important: the direction of movement. Whether running through a forest or flying at low altitude, we are visually aware of which way we are traveling relative to the environment.

If we regard shape, orientation, and scale as three types of 3-D information necessary for flying relative to the terrain, we may approach the problems of improving the terrain simulation in these terms. The approach is as follows.

The Basic Approach

The visual deficiencies of the LLF simulation would be cast in terms of shape, orientation, and scale. In other words, one would ascertain where the performance problems lie in simulated LLF flight, to what extent the cause is inadequate perception of the shape of the terrain (Is that ridge sharp or is it smoothly rounded? What does the terrain do over to the right?), inadequate perception of orientation (Is the aircraft yawing? Is the ground ahead rising or horizontal?), and inadequate perception of scale (How high am I above the ground? How far is the ridge?). Insight into the underlying problems cast in these terms might be gained by many means. Pilots might even be verbally examined in these terms, because we all have a strong (and similar) understanding of what is meant by shape, orientation, and scale. It was mentioned earlier that pilots commonly remark that judging altitude is difficult. That, for instance, is a matter of scale.

In addition to direct interview, there should be more quantitative psychophysical means for determining what 3-D information is deficient, but again, cast only in terms of shape, orientation, and scale, without attempting to uncover what "depth cues" are missing from the CIG display.

Note that we seem to attack what has been a thorny problem with only very informal and casual terminology. But the rigor comes later, when we apply knowledge about visual perception to suggest improvements to scale, or whatever. We will see an example of this analysis when we discuss how shape is perceived from undulating surface contours. This would have importance in the CIG depiction of rolling terrain. First it will be useful to examine a wide range of visual processes so that we begin to sort out which processes concern shape, which concern orientation, and so forth. In a sense, we are abandoning the rather simple notion of "depth cue" for three types of surface information, not just depth. This has proven useful in vision research proper. To illustrate, stereopsis is not merely a "cue" to depth but also of shape, at least; shading also provides shape information but tells us nothing about scale (the shading of the moon is similar to that of an orange). We cannot expect a simple correspondence between process and either shape, or orientation, or scale--vision is far too intertwined to be cast in such simple terms. But on the other hand, if we know that we need additional information about shape, we have many visual means for providing that information. It goes without saying that our understanding of vision is not sufficiently complete as to provide ready-made recipes for improving the simulation.

As a final introductory remark, note that although we might treat scale, orientation, and shape as substantially independent topics, we will probably find that improvements to the CIG display intended to enhance, say, the perception of shape will also improve the apparent orientation, and so forth. These side effects would be welcomed, of course. But the general strategy is to understand how one gains a perception of shape, orientation, and scale in order to increase the effectiveness of the simulator in inducing those perceptions.

Shape: What Are the Sources?

There are several potential sources of information about the shape of a surface, including binocular disparity from stereopsis, visual motion, shading, texture gradients, and surface contours. Let us consider each in turn.

First, although stereopsis provides an acute sense for 3-D shape in our usual environment, it is not useful for large-scale shape perception, e.g., of terrain a few miles away. The reason is that only the very near terrain causes detectable stereo disparities, and since that portion of the scene is also moving across the field of view at high angular velocity, one must track some nearby surface feature; otherwise it is blurred. On the other hand, stereopsis cannot be ruled out as potentially determining scale, especially in the foreground (see later).

Motion: Parallax, Optic Flow, and Shear Visual motion provides one of the dominant sources of information about shape. Several different aspects of motion have been distinguished, such as "shear" (discontinuities in projected angular velocity which arise, for example, along the edge of a physical object seen against a relatively distant background), "optic flow" (the wide-field visual effect from movement through the environment), and "motion parallax" (the changing projection of an object as it moves relative to us, from which we infer its 3-D shape).

Before discussing these aspects of motion, we reiterate that visual motion across the CIG display comes automatically when the 3-D model is transformed by perspective projection while "continuously" (i.e., at a sufficient rate) updating the viewer's position in that model according the speed and direction of motion relative to the model. Thus motion per se is given; it is what is in motion across the CIG display that is relevant to our discussion. For instance, are moving dots sufficient? (Luminous dots are particularly "cheap" to display on many CIG systems, whereas surface patches are in relatively short supply.)

In fact, moving dots are effective: if a collection of 3-D points in some rigid arrangement (such as the runway marker lights and the lights of nearby buildings and streets) are projected in motion on the display as if we were moving relative to them (as in landing), the visual interpretation in 3-D is remarkably precise.[6] Of course, the designers of visual simulator night displays have long been familiar with this. Note the 3-D shape is accurately perceived, but not the scale, unless there are familiar cues such as the runway width (see later).

So we know that points are sufficient stimuli, but what about lines and edges? What do they contribute over mere points of light? This perceptual issue has not been fully unraveled, but some relevant observations may be made. Our visual processes seem to require distinct and traceable image points in order to derive a 3-D shape, but a curve or line only offers the endpoints or points of discontinuity in tangent; arbitrary intermediate points along the curve cannot be tracked (see Ullman, 1979). Incidentally, this suggests that only the corner points of the checkerboard pattern (popularly used to depict terrain) contribute useful input to the motion interpretation process.[7]

When traveling across a textured surface there is an apparent streaming of detail across the visual field, commonly termed optic flow. This is regarded as a wide-field phenomenon, while the previously discussed motion parallax is detailed and foveal. What 3-D information is derived from optic flow in the periphery? Some hypotheses have been forwarded that the optic flow specifies distance up to a scalar (Gibson, 1950; Nakayama and Loomis, 1974) and even local surface orientation everywhere across the image (Koenderink and van Doorn, 1976). Those two proposals suggest that optic flow provides shape (but not scale) information, but they are largely theoretical; it remains to be seen what sort of 3-D information is derived, in fact, by the human visual system. It is possible that negligible shape information is derived from the periphery, even under the best conditions. Optic flow, particularly in the case of LLF, may provide only information about orientation and the direction of travel (this is discussed further later).

Another aspect of visual motion is motion shear. Whenever an opaque surface feature protrudes above the mean surface level, it occludes from view that which is behind it. Occlusion thereby provides information about relative distance--it allows us to partition the visual world into surfaces segregated by distance. This is particularly striking in LLF when the relative motion of nearby ridges against the background terrain causes them to be seen in relief. Since shear contributes to the apparent terrain shape, it deserves study. In particular, the questions of what is shearing and whether it is a simple dot pattern or edges or lines is of importance to CIG design. The perception of 3-D shape from motion was only briefly sketched here. It is hoped that it shows that while studying the perceptual processes one can also derive specific implications for CIG display.

---

[6] See Ullman (1979) for a theorem showing how this interpretation is feasible solely by analysis of the images without requiring higher-level knowledge.

[7] But that does not mean one can replace the checkerboard with dots (placed where each corner was) and have an equally compelling 3-D impression. The checkerboard also provides a useful texture gradient, at least. This demonstrates a difficult aspect of this work: visual processes and their visual inputs are largely intertwined.

Shading, Texture Gradients, and Contours We have considered the dynamic aspects of the visual display. The other side of the coin is the static properties which carry information about shape. These include shading, texture gradients, and contours that lie across the surface.

The apparent 3-D shape of a surface is usually enhanced when shaded. The interpretation of shading information is analytically a very difficult problem requiring knowledge of the illuminant directions, the reflectance functions of the various surfaces, and means for dealing with complex shadowing and mutual illumination conditions (Horn, 1975). But the human visual system probably does not attempt such a solution; instead, it extracts weaker inferences of 3-D shape that would be true without having to know the lumination conditions and the particular reflectance properties of the surface. This probably explains the success of even crude approximations to real shading that are adopted by CIG systems. Further research into human perception of shading should lead to an understanding of just how simple an approximation to shading can be effective in the simulator display.

Another source of 3-D information, which we will discuss only briefly, is the texture gradient. A homogeneous distribution of physical texture across a surface results in a texture gradient in the image. Because of perspective projection, the image texture in every locality is both foreshortened and scaled. We can recover shape information (specifically distance up to a scalar) from the texture gradient, but as discussed earlier, probably not from texture density. Further research is needed to determine how texture gradients are measured in order that we may gain insight into how best to depict texture for CIG display.

Contours that lie across a surface, as depicted in figure B-1a, are useful for inferring the shape of the surface. To make sense of the contours in the image, however, we must make certain assumptions about their geometry; see Stevens (1981) for the theory of surface contour sketched here. We will turn this to our advantage by ensuring that those assumptions are not violated when modeling terrain by means of contours.

Observe in figure B-1a that the lines appear drawn across an undulating surface. The basic assumption that we make is that the curvature of the lines reflects surface curvature.[8] It is as if the lines were straight lines on a carpet that became curved because the carpet was rippled. More formally, these contours are geodesics with the additional property of being lines of greatest curvature (see Hilbert and Cohn-Vossen, 1952, for a lucid discussion of these concepts).

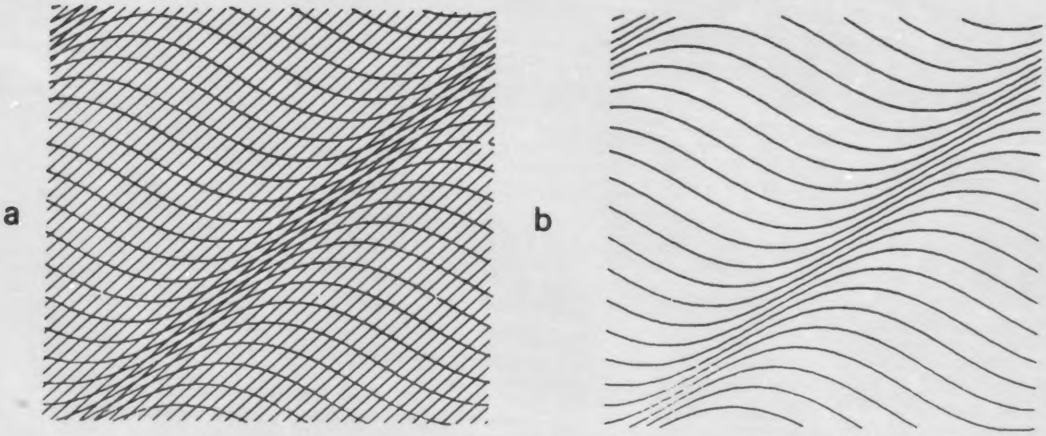


FIGURE B-1 The curved surface in (a) resembles a rippled carpet. The straight lines lie parallel to the ridge, the curved lines are perpendicular. The curved lines are lines of greatest curvature and planar; the straight lines are lines of least curvature. Note that the curved lines alone tell us a great deal about the shape of the surface (b), but the straight lines alone carry virtually no information.

A line of greatest curvature may be thought of as a path across a surface which experiences the greatest undulation. Note that in figure B-1b the straight lines that follow the ridges are perpendicular to the lines of greatest curvature. The straight lines are lines of least curvature and the surface is singly curved. The perpendicularity of the two curves is very important--it gives us constraint on the shape of the surface. Roughly speaking, our interpretation of surface contours probably embodies the following geometric reasoning (the various deductions follow from theorems in differential geometry, but they will not be elaborated upon here).

---

[8] Note that we do not easily see figure B-1 for what it is, a collection of lines on a flat sheet of paper. Instead, we interpret the undulation as having been caused by the underlying surface.

1. The physical curves are lines of curvature.
2. Intersecting curves meet at a right angle on the surface as a consequence of (1).
3. Where the surface contours are parallel, the surface is singly curved (like a rippled carpet).
4. Because of (1) and (3) the curves are geodesics and planar.

The above provides the likely basis for our perception of shape from surface contours in images such as figure B-1. Rigorous psychophysical verification of these conjectures remains to be performed, but informally our visual impression of shape is consistent with the geometric constraints 1 through 4. If that is the case, those constraints may also serve as the basis for design rules relevant to simulators, as described by the following.

When modeling terrain, especially undulating terrain, it is commonplace to use curves that resemble the edges of fields, roads, or fences. These curves carry information about the terrain shape just as figure B-1 does, but only if they are restricted geometrically in the manner that the human visual system implicitly assumes. That is to say, the curves that a simulator engineer lays in the terrain model should have the following restrictions:

1. Each curve should be planar, a line of curvature, and geodesic.
2. Any intersecting curves should meet at a right angle.
3. If the surface is singly curved, like a smooth ridge, it is only necessary to depict a few lines of greatest curvature (as in figure B-1a). The lines parallel to the ridge may be omitted in general.
4. If the surface is doubly curved, like a round hill, it is important to place lines of curvature at close spacing. It is best to include both sets of lines of curvature, so the surface appears to have a net draped over it (figure B-1a). Each intersection will then be a right angle, and the surface shape will be readily apparent.

These are a few rules which should be followed. Note that they may be "broken" and we might still correctly perceive the surface from motion, just as we can understand a strange piece of sculpture by walking about it and seeing it from different perspectives. For instance, suppose a ridge were depicted by a contour that climbs over it, but instead of following a line of greatest curvature (the "fall line" as a skier would put it) it climbs obliquely over the ridge. At a glance that curve would mislead us--we would see the surface shape incorrectly, but with changing viewpoints we might later see the surface correctly and understand that the curve is not what we assumed.

Depicting surface shape by undulating lines, as just discussed, should be compared with the method of using checkerboards. First of all, checkerboards have been proposed because they are relatively economical in terms of edges, and squares seen in perspective are easily interpreted in 3-D. A checkerboard pattern, in fact, is probably optimal for depicting a planar surface, given the current limitations in displayable edges. But the straightforward extension of checkerboards to indulating surfaces may not be the best approach. First let us consider singly curved surfaces--ripples in a carpet. Checkerboard patterns are useful for ridges so long as the rows are arranged parallel with the ridge. In that case we have the geometric arrangement of figure B-1b where the edges of the squares that are parallel with the ridge (in other words, those that lie at constant elevation) are lines of least curvature, and the other edges climb over the ridge. But as stated earlier, the lines of least curvature may probably be omitted because they are redundant. In terms of edges, then, a series of stripes, rather than checkers, would be more economical and probably would be equally effective. For a doubly curved surface such as a round hill, the problem becomes somewhat more difficult, but it is solvable if sufficiently fine stripes or checkers are used. That is because a doubly curved surface, if sliced fine enough, can be treated as singly curved in general. Incidentally, the line defined by a column or row of checker squares has alternating contrast along its length. This tends to break up the lines, for the visual system has difficulty in aggregating into a line elements with opposite contrast sense. The checkerboard pattern is unlikely treated as a collection of long surface contours, therefore. Instead, each white or black square is seen disjointly. For that reason, long stripes or lines may be more useful in depicting undulating terrain.

Sources of Information About Orientation

The previous discussion covered the major sources of visual information about surface shape. Next we will discuss orientation. This discussion is more difficult, because 3-D shape is most naturally described relative to the viewer and therefore in representing shape one simultaneously captures several aspects of orientation. For instance, recall that in the night landing simulation, motion parallax involving mere luminous dots on a dark background can give a compelling impression of movement toward the solid earth during landing. Clearly we perceive the orientation of the terrain as well as its shape. While orientation and shape are intertwined, it is useful to approach visual processing from one or the other perspective, depending on the need.

The direction of movement and one's spatial orientation are two forms of orientation information that are relatively distinct from shape. Both are difficult to visually determine in LLF since uneven terrain often prevents one from using a distant horizon as an altitude reference. But optic flow seems useful (Gibson, 1950), particularly in LLF, where the terrain appears smeared and blurred (see Harker and Jones, 1980). However, the highly simplified CIG displays might not provide sufficiently dense surface texture moving with sufficient smoothness of motion to be effective. Again, we see that further research is needed to see how optic flow is visually processed. This research problem is of particular importance to LLF. A final point regarding optic flow should be made. Simply because the ground texture appears blurred and streaky in LLF does not mean that one can display a simple pattern of streaks in the periphery displays. When one tracks a detail on the ground, it becomes roughly stationary on the retina and the smearing of detail vanishes. We do not know what role tracking eye movements would play in LLF (certainly they are important when scrutinizing ground targets, but what importance they have in the basic problem of flying LLF is not yet known).

A local "cue" to orientation which has been incorporated in CIG displays is the simple geometric arrangement of two lines or edges that intersect at right angles on the surface (figure B-2a). It is straightforward to show that the image of a right angle (which because of foreshortening in the perspective projection appears as an obtuse angle) carries some information about the surface orientation, but it alone does not specify a unique 3-D orientation; it could theoretically correspond to a large variety of differently oriented planes in 3-D. Additional constraint comes from assuming that the two lines are equal length in 3-D.[9] Note that these two constraints--perpendicular intersections and equal length segments--are neatly combined in the square checkerboard patterns which are often used in terrain simulation. Perpendicular intersections in general are useful indicators of surface orientation, provided the lines or edges are of equal length on the surface.

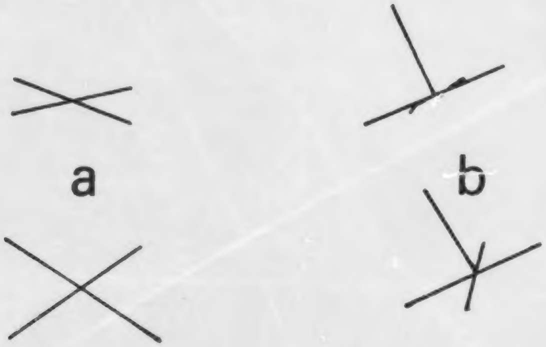


FIGURE B-2 The intersecting lines in (a) appear to lie on planar surfaces in 3-D. The interpretation involves assuming the intersection is perpendicular and the two lines are of equal length on the surface. The intersections in (b) may be thought of as a signpost at a street intersection seen from different viewpoints. To interpret this configuration, it is necessary only to assume the intersecting lines are mutually perpendicular in 3-D.

---

[9] There is still an ambiguity of the Necker cube variety. But when viewing this configuration within the larger context of the ground plane, that ambiguity is resolved.

A point that has seldom been emphasized is that a trihedral intersection, three mutually perpendicular lines (figure B-2b), actually carries enough information in its image to fix its surface orientation precisely.[10] The arrangement resembles a signpost at a street intersection--note that the line segments no longer need to be equal length in 3-D. This configuration would be a very effective means for indicating orientation, even scattered across an otherwise featureless terrain.

Sources of Information About Scale

Now let us suppose that the terrain simulation is adequate in terms of shape and orientation. The problem that would remain is to ensure that the pilot can judge the distance to the surface and his altitude above it with sufficient accuracy. What are the sources of information about scale that he might utilize? Scale may be inferred by several perceptual methods: directly from stereopsis or indirectly from the known size of recognizable objects, from known velocity, and several other methods that we will discuss. Scale is certainly necessary for various flying tasks; the difficulty that pilots often have in landing amphibious planes on water and maintaining low-level flight over water and sand dunes suggests that there are real visual scenes that are deficient in information about scale.

Stereopsis Stereopsis may, in theory, have a minor contribution at low altitude, but to see this we need to be somewhat quantitative for a moment. Of course, stereopsis is most useful in the very near environment (distances of less than 30 feet), but we are sensitive to stereo disparity out to roughly 1,800 feet (computed from a stereoacuity of 24 arc seconds (Graham et al., 1949)). Hence we cannot dismiss the possibility that stereopsis provides a pilot altitude information when flying LLF (some pilots reportedly look out of the side canopy to judge their altitude (Harker and Jones, 1980)). At roughly 100 feet in altitude, one can see downward sufficiently well to be viewing surface detail within the useful range of stereopsis (Kennedy and McKechnie, 1970), but because of the blurring and streaking which we have discussed, unless the pilot tracks some feature on the ground, stereopsis would probably fail. But a significant impression of depth might be derived, provided one tracks a surface feature for sufficient time to achieve stereopsis before it is out of view. Consider an aircraft traveling 500 knots at 100 feet and a surface feature that passes within 500 feet of the aircraft at nearest approach. One may easily compute that approximately two seconds elapse from the time the point enters stereo range (1,800 feet) to when it passes directly by the side of the aircraft. Hence, if a pilot in low-level flight has the time to visually track a surface feature during the time it is within stereo range, stereopsis could conceivably provide useful scale range. It must be stressed, however, that head movements would be required to track the surface feature, the visual tracking task would not be easy in a hostile environment, and stereopsis under those visual conditions has not received sufficient psychophysical study.

---

[10] Again, up to a Necker reversal which can be disregarded here.

There is evidence that casts doubt on this hypothesis, however. The evidence is simple: recall that certain types of terrain are particularly difficult to fly over at low level--specifically, sand dunes and open water. There is sufficient viewing time to achieve binocular fusion, sufficient visible detail on which to establish stereo fusion, and a large region of the surface is within stereo range at low altitude. Nonetheless, LLF is difficult over that terrain. Apparently the sense of scale (if any) that one derives from stereopsis is insufficient for making the critical altitude judgments. Stated another way, stereopsis may play some role in LLF, but it is probably insignificant. It must be said, however, that the above is not conclusive--the issue deserves careful experimental consideration.

Known Size One method to infer distance is from the measured retinal size of an object of known size. It is well known that the distance to an object varies inversely with the angle it subtends. Theoretically, if one knew that a tree were 20 feet high, one could also know its absolute distance on the basis of its retinal size. Certainly the visual system capitalizes on this relation, and we even consciously search a novel scene for some cue to its scale (conscious attention is not required, as Helmholtz (1925) recognized in his terming it "unconscious inference"). There are phenomena which strongly suggest that we do infer distance from known size (e.g., Enright, 1970).

However, empirical studies of "size constancy" and absolute distance perception (Epstein and Landauer, 1969; Gogel, 1971; Hochberg, 1971; Rock and McDermott, 1964) have shown that the psychophysical relation between distance and retinal size is not as simple as might be expected. This is one place where simulator designers have experienced difficulty in interpreting the psychological literature. Many of the experiments were performed in artificially restricted viewing situations (e.g., darkened rooms with few reference objects) and those that were performed "in the field" would involve verbal judgments of distance, e.g., as a target being so many feet away (Gibson and Bergman, 1954) or comparison judgments between two distances (Foley, 1972). Few experiments reveal just how precisely we perceive the scale of the visual world from objects of known size.

It must be stressed that we are ultimately concerned with the visual judgments of absolute distances, and therefore with providing sufficient information so that the pilot can fly 100 feet above the terrain, for instance. The known-size method probably plays a role in this ability. This is another place where tightly directed investigation is critically needed.

Known Velocity A potentially useful method for computing scale is quite similar to the known-size method just discussed. If one knows the velocity of travel past an object, one can infer the distance to that object from the induced angular velocity (e.g., retinal velocity given a fixed gaze, or velocity relative to some point on the cockpit canopy). The following relation between absolute distance d, absolute velocity V, and angular velocity ω was pointed out by Gibson and others (Gibson, 1950; Nakayama and Loomis, 1974):

$$d = \frac{\underline{V}\sin\beta}{\omega} \tag{1}$$

where β is the angle from the direction of travel to the given point whose distance is to be measured. The relation presumes that the given point is stationary and the viewer is in pure translation. It is powerful in that it allows one to compute a depth map for the entire visual field (everywhere there is detail moving across the field of view) in terms of ω and β (measurable, in theory) and the single unknown V. That depth map would specify absolute distance if the absolute velocity V were known.

Conscious deduction is not necessary or even likely in this process. Instead, a pilot experienced in flight at low altitude and high velocity might come to expect a particular angular velocity in the periphery, in a manner analogous to driving a car and expecting the road to slip by at an appropriate rate for any given driving speed.[11] Then if the groundspeed is held constant but the altitude is lower than normal, the angular velocity would be higher than normal, and vice versa. This relation could, theoretically, account for the precision with which altitude may be held in LLF by experienced pilots. It is not inconceivable that part of the skill that a pilot acquires through flight training is the unconscious calibration of retinal velocity according to ground speed and altitude, and furthermore the development of an effective feedback loop that attempts to control altitude according to actual retinal velocity at any instant.

It should be relatively straightforward to establish whether this is the case. The direct relationship between altitude and groundspeed predicts that as speed increases there should be a tendency to increase the cruise altitude, other factors being constant. The following evidence (J. Richter, personal communication) suggests that this occurs. Interestingly, it is most apparent when flying over open water (the situation we noted before as difficult). Perhaps the fact that water provides little evidence of scale, compared to a richly textured rural terrain containing familiar surface features, allows one to observe the weaker contribution of the known speed method. Over the ground, one's altitude tends to remain fairly constant as speed increases, but over water the altitude definitely tends to climb as the aircraft is accelerated. It is consistent with there being some unconscious process attempting to maintain an expected angular velocity, where an increase in angular velocity is attributed to a loss of altitude rather than an increase in ground speed. These informal reports suggest that the known velocity method for computing scale may have some validity in actual flight, and therefore should be given careful experimental investigation. The experiments should probably be performed using unfamiliar surface textures to examine the relationship between speed and altitude. The problem must be addressed in conjunction with an investigation of texture, as undoubtedly the effect will vary in magnitude with texture variations.

---

[11] It is noteworthy that when changing from a passenger car to a low sports car the apparent speed is greater merely because of the larger angular velocities associated with being nearer the ground.

Other Methods In addition to the two methods just discussed, there are other geometrical methods for gaining scale information. Several have been discussed by Harker and Jones (1980). Typically they consist of some geometric quantity--e.g., the ratio of angle subtended by some vertical surface feature compared to its angular distance below the horizon--from which one may judge whether the altitude is maintained constant, or whether the aircraft will clear a vertical obstacle.[12] While strictly speaking these geometric quantities do not specify scale in the sense we mean, they are, nonetheless, potentially useful in flying. We probably should distinguish between qualitative problems that can be solved geometrically (such as obstacle clearance and maintaining constant altitude) and quantitative problems (such as clearing obstacles by so many feet, maintaining a particular altitude, and so forth). But it is not certain which sort of problem, the qualitative or the quantitative, deserves the greater attention at the moment.

Sketch of an Application of the Computational Approach

To illustrate a specific example of using the computational approach to improving the CIG simulation of terrain, consider the depiction of undulating terrain for LLF. We focus on the problem of improving the visual information about the shape of the terrain, which of course is but one aspect of the overall effort of generating an effective LLF visual simulation.

Reflecting on the various sources of visual information about shape, we recall that these include visual motion (of surface features due to one's movement over the terrain), shading, texture gradients, and surface contours. Suppose we focus more closely on the contributuion that surface contours make to the apparent shape of the terrain. That is, let us consider how one might make terrain features such as ridges or valleys visually apparent by essentially painting contours (perhaps depicting property boundaries or roads) across the CIG terrain model.

---

[12] Some are well known and supposed to be consciously attended to. For instance, if the top of a tower is climbing in the visual field it is above the flight path and will not be cleared.

The results of theoretic analysis of surface contour perception were sketched earlier. Basically, our 3-D interpretation of contours embodies particular assumptions about the geometry of these contours and their relation to the surface across which they lie. The assumptions include (see earlier and Stevens, 1981):

1. The physical curves are lines of curvature.
2. Intersecting curves meet at a right angle.
3. Parallel contours imply the surface is singly curved.
4. The physical curves are geodesic and planar.

If those geometric assumptions are indeed those governing human perception of contours, that suggests a means for placing contours across CIG terrain models so that they are visually effective (recall the four "design rules" for surface contours described earlier).

The next step, therefore, is careful psychophysical study that verifies that surface contour perception involves the geometric assumptions that were established on purely theoretic grounds. Specifically, consider item 4 above. If our perceptual apparatus incorporates the assumption that a viewed curve is planar and geodesic (in the absence of information to the contrary as provided by, say, stereopsis and motion), that assumption has predictable and testable consequences. What would be required next, therefore, is empirical investigation. Once we have established the role of these (or other)geometric assumptions, a quantitative study is required of the relative importance of such factors as contour spacing, line width, and so forth.

Concluding Remarks

Three types of 3-D information that must be gathered by the visual system in order that a pilot might fly close to the terrain are its scale, shape, and orientation. The visual deficiencies of the LLF simulation can be discussed in such terms. Indications are that scale information requires the greatest improvement.

More rigorous analysis comes next. We gain insight into improving the display by learning how the human visual system determines scale, for example. There are many sources of scale information, but much more effort is required before we can make concrete suggestions regarding CIG improvements.

We did see an example of where the computational analysis of surface contours, a source of shape information, leads to rather specific suggestions regarding the visual display. For our visual systems to make sense of image curves in terms of actual contours lying across physical surfaces, a number of geometric assumptions have to be made. Analyzing what these might be, in theory, coupled with psychophysical verification that those particular assumptions are involved in our interpretation process and not some other set of assumptions, leads to some design rules, as it were. The design rules are intended for the simulator engineer who depicts terrain using curves (one curve might be meant to depict a fence over a hill, another might depict the edge of a field). It is of course important that the pilot perceive the simulated world in the way that it was intended by the designer. To do so, the contours placed in the terrain model should be restricted in their geometry so that they match the geometric assumptions that govern their visual interpretation.

The surface contour example is a particularly clean demonstration of how understanding some aspect of vision has application to simulation. As should be evident from the previous discussions, much needs to be learned about vision.

REFERENCES

Attneave, F.
1972 Representation of physical space. In A. W. Melton and E. Martin, eds., Coding Processes in Human Memory. New York: John Wiley.

Braunstein, M.
1968 Motion and texture as sources of slant information. Journal of Experimental Psychology 78:247-253.

Braunstein, M., and Payne, J. W.
1969 Perspective and form ratio as determinants of relative slant judgments. Journal of Experimental Psychology 81:584-590.

Enright, J. T.
1970 Distortions of apparent velocity: a new optical illusion. Science 168:464-467.

Epstein, W., and Landauer, A. A.
1969 Size and distance judgments under reduced conditions of viewing. Perception and Psychophysics 6:269-272.

Finch, D.
1977 Hyperbolic geometry as an alternative to perspective for constructing drawing of visual space. Perception 6:221-225.

Foley, J. M.
1972 The size-distance relation and intrinsic geometry of visual space: Implications for processing. Vision Research 12:323-332.

Gibson, J. J.
1950 The Perception of the Visual World. Boston: Houghton Mifflin.

Gibson, J. J.
1979 The Ecological Approach to Visual Perception. Boston: Houghton Mifflin.

Gibson, J. J., and Bergman, R.
1954 The effect of training on absolute estimation of distance over the ground. Journal of Experimental Psychology 48:473-482.

Gogel, W. C.
1971 The validity of the size-distance invariance hypothesis with cue reduction. Perception and Psychophysics 9:92-94.

Graham, C. H., Riggs, L. A., Mueller, C. G., and Solomon, R. L.
1949 Precision of stereoscopic settings as influenced by distance of target from a fiducial line. Journal of Psychology 27:203-207.

Grimson, W. E. L.
1980 Computing Shape Using a Theory of Human Stereo Vision. Unpublished PhD thesis. Department of Mathematics, Massachusetts Institute of Technology.

Haber, R., and Hershenson, M.
1980 The Psychology of Visual Perception. 2nd ed. New York: Holt.

Harker, G. S., and Jones, P. D.
1980 Depth Perception in Visual Simulation. AFHRL-TR-80-19.AD-A087 828. Williams AFB, Ariz.: Air Force Human Resources Laboratory.

Hennessy, R. T., Sullivan, D. J., and Cooles, H. D.
1980 Critical Research Issues and Visual Systems for a V/STOL Training Research Simulator. Technical Report NAVTRAEQUIPCEN 78-C-0076-1. Orlando, Fla.: Naval Training Equipment Center.

Helmholtz, H.
1925 Physiological Optics. Vol. 3 (3rd ed., translated by J. P. Southall). New York: Optical Society of America.

Hilbert, D., and Cohn-Vossen, S.
1952 Geometry and the Imagination. New York: Chelsea Publishing.

Hochberg, J.
1971 Perception II: Space and movement. In J. W. Kling and L. A. Riggs, eds., Woodworth and Schlosberg's Experimental Psychology, 3rd ed. New York: Holt, Rinehart and Winston.

Horn, B. K. P.
1975 Obtaining shape from shading information. In P. H. Winston, ed., The Psychology of Computer Vision. New York: McGraw-Hill.

Kennedy, K. W., and McKechnie, D.
1970 Visibility Toward the Ground from Selected Tactical Aircraft. Technical Memorandum AMRL-TR-69-123. Wright-Patterson AFB, Ohio: Air Force Aerospace Medical Research Laboratory.

Koenderink, J. J., and van Doorn, A. J.
1976 Local structure of movement parallax of the plane. *Journal of the Optical Society of America* 66:717-723.

Kraft, C. L., Anderson, C. D., and Elworth, C. L.
1980 *Psychophysical Criteria for Visual Simulation Systems*. Final Report, AFHRL-TR-79-30. Williams AFB, Ariz.: Air Force Human Resources Laboratory. AD-A084 776.

Marr, D.
1976 Early processing of visual information. *Philosophical Transactions Royal Society, London* B 275:483-524.

Marr, D.
1978 Representing visual information. *Lectures on Mathematics in the Life Sciences* 10:10-180. (Also available as MIT A.I. Lab. Memo 415.)

Marr, D.
1981 *Vision: A Computational Investigation into the Human Representation and Processing of Visual Information*. San Francisco: W. H. Freeman (in press).

Marr, D., and Hildreth, E.
1980 Theory of edge detection. *Proceedings of the Royal Society of London* B 207:187-217.

Marr, D., and Nishihara, K.
1978 Representation and recognition of the spatial organization of three-dimensional shapes. *Philosophical Transactions of the Royal Society of London* B 200:269-294.

Marr, D., and Poggio, T.
1977 From understanding computation to understanding neural circuitry. *Neuroscience Research Progress Bulletin* 15(3):470-488.

Marr, D., and Poggio, T.
1979 A computational theory of human stereo vision. *Proceedings of the Royal Society of London* B 207:301-328.

Mayhew, J. E. W., and Frisby, J. P.
1981 Psychophysical and computational studies towards a theory of human stereopsis. *Artificial Intelligence*, 17: 349-385.

Nakayama, K., and Loomis, J. M.
1974 Optical velocity patterns, velocity-sensitive neurons, and space perception: A hypothesis. *Perception* 3:63-80.

Purdy, W. C.
1960 The Hypothesis of Psychophysical Correspondence in Space Perception. Technical Information Series, No. R60ELC56. Ithaca, N.Y.: General Electric Co.

Richter, J., and Ullman, S.
1980 A model for the spatio-temporal organization of x and y-type ganglion cells in the primate retina. MIT A.I. Laboratory Memorandum 573. Cambridge, Mass: MIT.

Rock, I., and McDermott, W.
1964 The perception of visual angle. Acata Psychologica 22:119-134.

Semple, C. A., Hennessy, R. T., Sanders, M. S., Cross, B. K., Beith, B. H., and McCauley, M. E.
1980 Aircrew Training Device Fidelity Features. AFHRL-TR-80-36. Wright-Patterson Air Force Base, Ohio. Advanced Systems Division, Air Force Human Resources Laboratory. AD-A094 665.

Smith, O. W., and Smith, P. C.
1957 Interaction of the effects of cues involved in judgments of curvature. American Journal of Psychology 70:361-375.

Stevens, K. A.
1980 Surface perception from local analysis of texture and contour. MIT A.I. Laboratory Technical Report 512. Cambridge, Mass.: MIT.

Stevens, K. A.
1981 The visual interpretation of surface contours. Artificial Intelligence 17:47-73.

Ullman, S.
1979 The Interpretation of Visual Motion. Cambridge, Mass.: MIT Press.

Ullman, S.
1980 Against direct perception. The Behavioral and Brain Sciences 3:373-415.

APPENDIX C

VISUAL SENSORY ASPECTS OF SIMULATION

One Example of an Experimental Approach[1]

D. M. Regan

Rationale

Several quite different strategies have been suggested for coming up with visual factors that might correlate with flying performance in a simulator or aircraft. These strategies range from multivariable factorial studies to the "natural computation" approach of the MIT group. This appendix outlines one candidate strategy for identifying visual sensory factors that are important in flight simulation. This approach runs along the following lines:[2]

1. Carry out basic research on the sensory aspects of vision, testing some specific hypotheses about how the eye processes visual sensory information.
2. From the results of this basic research, predict which visual functions will be important in simulation.
3. Test these visual functions in pilots, and correlate the test results with simulator (and aircraft) flying performance.

In order to focus our efforts, we have restricted ourselves to one of several possible hypotheses as a guide. The next section of this paper lists some of the resulting basic research findings and conclusions that might be relevant for simulation. The last section outlines two follow-up studies of simulator flying performance.

We should note that the theoretical approach used in these simulator studies is no more than a working hypothesis or guide.

---

[1] It is often noted that, in general, an increased basic understanding of visual function would help to improve simulator design. This appendix can be read as an account of one (among many) practical ongoing efforts along these lines, in which the same experimental thrust has been maintained over a ten-year period. The simulator studies outlined here could by no means have been carried through without generous help and advice from staff of the U.S. Air Force Human Resources Laboratory, Williams AFB and all flying personnel involved for Williams AFB, Nellis AFB, Luke AFB, and MacDill AFB.

[2] We appreciate that other, quite different, strategies have been used in the bulk of visual research on simulation.

Our theoretical approach has been firmly in the camp of those who use simple laboratory stimuli, often at threshold levels, with the aim of uncovering elementary functional subunits in the visual pathway (Braddick et al., 1978; Regan, 1982). If we wish to usefully predict vision in a complex visual environment, we should search for subunits that analyze retinal image information into more or less orthogonal (nonoverlapping) elements. However, it is not necessary that a given subunit be linear.

Examples of Basic Research Findings and Conclusions with Possible Implications for Simulator Design

The optical flow pattern generated by an observer's movement contains information about the direction of movement (Gibson, 1950, 1958; Richards, 1975). It has been sometimes suggested that an observer could determine his projected impact point from the center of expansion of his retinal flow pattern; however, there is reason to think that in practice this cannot be done (Llewellyn, 1971; Regan and Beverley, 1981). If the observer fixates his gaze off to one side away from his direction of movement, the retinal flow pattern will be distorted (Regan and Beverley, 1981; Richards, 1975). On the other hand, subjects can accurately judge where, on the retinal image, the local magnification is changing most rapidly, and in some situations this direction coincides with the direction of self-motion (Regan and Beverley, 1981). There is evidence that visually judging the direction of self-motion on the basis of visual flow patterns may involve selective sensitivity to changing size (Regan and Beverley, 1979a).

In order to explain certain experimental data, we theoretically proposed that the human eye responds to an object's rate of change of size more or less independently of the object's motion in the frontal plane (Regan and Beverley, 1978, 1980). Note that an object's rate of change of size is closely related to its line-of-sight component of velocity. In particular, the response of the eye's changing-size subsystem may directly indicate time to collision, more or less independently of the observer's trajectory and of the object's trajectory.[3]

The human eye processes stereo position in depth separately from stereo motion in depth; in addition to the classical stereoscopic depth mechanism sensitive to disparity, there is a second stereoscopic mechanism sensitive to the relative speed seen by the left and right eyes. Physiologically, there are different types of brain cells predominantly sensitive to disparity and stereo motion in depth (Regan et al., 1979; Richards and Regan, 1973).

A sensation of motion in depth can be produced either by stereoscopic (binocular) stimulation or by changing size. Relative visual sensitivity to the binocular and to the monocular cues does not much depend on viewing distance (contrast with classical stereo vision).

---

[3] That (Time to Collision) = (Object's Fractional Rate of Change of Size)$^{-1}$ is easily shown for a nonrotating object.

Relative binocular to monocular sensitivity does, however, depend on the object's speed and linear size. This suggests that there is no general answer to the question, "What effect has closing one eye upon a pilot's ability to judge motion in depth?" (Regan and Beverley, 1979b).

Findings suggest that for motion-in-depth perception, static texture is worse than no texture (Beverley and Regan, submitted).

Correlations Between Visual Test Results and Simulator Flying Performance

This section describes two studies in which the results of visual tests on pilots were compared with flying performance on a flight simulator (A-10 aircraft) and with aircraft flying grades (T-38 jet trainer) at Williams AFB.

In the first study (Kruk et al., 1981), subject groups comprised twelve pilot instructors, twelve nonpilot weapons officers, twelve graduating student pilots, twelve first-year student pilots, and twelve nonmilitary nonflying subjects. A total of thirteen visual test measures were collected from each subject, including manual tracking of a target that moved in depth in the presence of vibratory "jitter" motion (Beverley and Regan, 1980). The simulator flying task was restricted visibility landing. In brief, the better the pilot's performance in tracking a target that moved in the frontal plane, the earlier was the first visual flight correction during landing. In addition, the number of crashes was predicted by tracking accuracy for a target that moved in depth. Since the only difference between the two tracking tests was visual, motor factors being common, and since the two tests correlated with different aspects of landing performance, we concluded that the two tracking tests detected intersubject differences in visual sensory factors that are important in landing (though intersubject differences in eye-hand coordination may well have been involved also). Quite different correlations were obtained between landing performance and psychophysical thresholds for motion and contrast. Since these correlations were weak, we concluded that these threshold tests failed to detect the performance-related intersubject differences in vision detected by the tracking tests.

Different individual subjects were used in a second study. Simulator flying performance was compared with the results of sensory visual tests for twelve experienced fighter pilots (group 1), twelve pilot instructors (group 2), and twelve graduating student pilots (group 3). The following is extracted from a report submitted for publication (Kruk et al., submitted for publication).

Flight Simulator Tasks

The A-10 cockpit of the Advanced Simulator for Pilot Training (ASPT) at Williams AFB was used throughout. The simulator was initialized 146 m behind an A-10 lead aircraft and the pilot instructed to close and assume fingertip right position until the simulator re-initialized after 2 min flight. This procedure was repeated for close trail and fingertip left positions, then the whole sequence was repeated with the horizon removed. Time spent in correct formation was measured. Groups 1 and 2 then flew a low-level exercise. Pilots were instructed to fly through a mountain pass and on for about 5000 m while maintaining an altitude of about 36 m, then pop up to about 360 m and execute a dive bomb attack on a specified target (one of five buildings near a road). Then the pilot flew about 3000 m at about 36 m altitude to exit the area. There were two SAM sites and two active antiaircraft artillery sites. Auditory tones indicated to pilots when they were being tracked by SAM radar, when a missile was launched and when a missile was close, respectively. Pilots were instructed that they were likely to be shot down if they flew above about 110 m for more than about 10 sec. Each pilot carried out this exercise six times. The SAM and AAA threats served to ensure that performance would be strongly influenced by visual factors, since low-level flight is heavily dependent on out-of-cockpit visual input. Moreover, since the target could not be seen from low altitude, visual judgments were important in judging when to pop up and in correctly placing the aircraft during the dive. Bomb aiming and release were entirely visual and under the pilot's control. The manual bomb delivery mode was employed so that accuracy was entirely determined by the aircraft's trajectory and speed at the moment of release. We measured the percent time tracked by missile radar, number of times shot down, number of crashes, number of bomb delivery hits and near misses (within 36 m radius), altitude and heading variations, variability in release height, and release "G."

Restricted visibility landings were carried out as described [in Kruk et al., 1981]. In brief, pilots were told that airspeed was 120 kts (62 m/s), glide slope 2.5°, and that the initial ILS (Instrument Landing System) flight path was randomly set to land 61 m to left or right of centre. Visibility was nominally 460 m so that the runway was invisible early in the approach. Pilots were instructed to land on each approach, and each pilot completed six landings. We measured the number of crashes, and the distance from runway threshold at which the first visual flight correction was made.

Visual tests comprised superthreshold velocity discrimination of a radially expanding flow pattern, manual tracking of both motion in depth and motion in the frontal plane, motion thresholds and contrast thresholds for a moving square, and a static sinewave grating.

Landing and formation flight performance correlated with both manual tracking and expanding flow pattern test results. Pilots who were better able to discriminate different rates of expansion of the test flow pattern achieved a greater percentage of hits and near misses in the low-level flight and bombing task. Aircraft flying grades for student pilots correlated with expanding flow pattern test results and with manual tracking of motion in depth.

Implications for Simulator Design and Pilot Selection Tests

Of the 13 threshold and superthreshold test measures, tests of superthreshold visual sensitivity to motion correlated most strongly with simulator and aircraft flying performance. This indicates that intersubject differences in the physiological processing of motion were an important determinant of intersubject differences in flying performance on our particular tests. Our findings suggest that motion tests (e.g., the changing-size tracking test and superthreshold velocity discrimination) might, perhaps, be usefully added to the present, mainly static, battery of visual tests used in selecting flying personnel. Our findings also suggest that the transfer of training from simulator to aircraft flying tasks, including low-level flight, restricted visibility landing and formation flight, might be enhanced by placing more emphasis on improving the accurate, artifact-free representation of motion in simulator visual displays as compared with the historical emphasis on improving static spatial factors such as resolution and number of edges.

Ongoing Research

In cooperation with Yuma Range and Williams AFB we are currently working on extending the simulator studies to include performance measures in aircraft, with the aim of finding whether the visual factors we have identified as important in certain simulator flight tasks are also important in the air.

Some Suggested Experiments

1. Define the role and important parameters of expanding flow patterns in judging the direction of self-motion (e.g., spatial frequency and dynamic requirements).
2. Find whether visual sensitivity to stereo motion-in-depth is involved in low-level flight in fixed-wing aircraft and helicopters.
3. Define the role of visual sensitivity to changing size in low-level flight.
4. Define the role of visual sensitivity to texture shear in recognizing objects and judging distance in flying environments, including nap-of-the-earth operations.

REFERENCES

Beverley, K. I., and Regan, D.
1980 Device for measuring the precision of eye-hand coordination when tracking changing size. *Aviation, Space and Environmental Medicine* 51:688-693.

Beverley, K. I., and Regan, D.
Texture versus size changes in stimuli for motion-in-depth. Submitted for publication.

Braddick, O., Campbell, F. W., and Atkinson, J.
1978 Channels in vision: Basic aspects. In R. Held, H. W. Leibowitz, and H.-L. Teuber, eds., *Handbook of Sensory Physiology*. Vol. 8. New York: Springer.

Gibson, J. J.
1950 *The Perception of the Visual World*. Boston: Houghton Mifflin.

Gibson, J. J.
1958 Visually controlled locomotion and visual orientation in animals. *British Journal of Psychology* 49:182-194.

Kruk, R., Regan, D., Beverley, K. I., and Longridge, T.
Correlation between visual test results and flying performance on the Advanced Simulator for Pilot Training (ASPT) - II. *Human Factors*, submitted for publication.

Kruk, R., Regan, D., Beverley, K. I., and Longridge, T.
1981 Correlations between visual test results and flying performance on the Advanced Simulator for Pilot Training (ASPT). *Aviation, Space and Environmental Medicine* 52:455-460.

Llewellyn, K. R.
1971 Visual guidance of locomotion. *Journal of Experimental Psychology* 91:245-261.

Regan, D.
1982 The concept of visual channels: Its relevance to ophthalmology and the performance of skilled tasks involving eye-limb coordination. *Psychological Review* (in press).

Regan, D., and Beverley, K. I.
1978 Looming detectors in the human visual pathway. *Vision Research* 18:415-421.

Regan, D., and Beverley, K. I.
1979a Visually-guided locomotion: Psychophysical evidence for a neural mechanism sensitive to flow patterns. *Science* 205: 311-313.

Regan, D., and Beverley, K. I.
1979b Binocular and monocular stimuli for motion-in-depth: Changing-disparity and changing-size inputs feed the same motion-in-depth stage. Vision Research 19:1331-1342.

Regan, D., and Beverley, K. I.
1980 Visual responses to changing size and to sideways motion for different directions of motion in depth: linearization of visual responses. Journal of the Optical Society of America 11:1289-1296.

Regan, D., and Beverley, K. I.
1981 How we avoid confounding the direction we are looking with the direction we are moving. Science (in press).

Regan, D., Beverley, K. I., and Cynader, M.
1979 The visual perception of motion in depth. Scientific American 241:136-151.

Richards, W.
1975 Visual space perception. In E. C. Carterette and M. P. Friedman, eds., Handbook of Perception. Vol. V. New York: Academic Press.

Richards, W., and Regan, D.
1973 A stereo field map with implications for disparity processing. Investigative Ophthalmology 12:904-909.

APPENDIX D

LOCOMOTION THROUGH VISUAL SPACE: OPTIC FLOW AND AND PERIPHERAL VISION

Ralph Norman Haber

The design of flight simulation displays for low-level flight must necessarily compromise a realistic presentation of the full visual scene unfolding before and beneath the pilot. It is simply not possible to provide even reasonable verisimilitude of detail over the entire visual field of the pilot at rates approaching the real time demands of flight. The faster the velocity and the lower the altitude, the more severe the compromise. And the compromise is extreme for low-velocity flight as well, though not because of real-time limitations. Of course, low-level flight simulation has been practical for a number of years, with the exercise of many compromises in how visual information is presented to the pilot. Most of these compromises have resulted from hardware limitations, and not necessarily including an analysis of how the human visual system processes information about locomotion through space.

In order to examine the impact of these compromises, especially in a context of the information human beings use to perceive visual space, the following is a brief visual task analysis that relates sources of visual information available in different flight tasks, especially those that can or do benefit from training in flight simulators.

Visual Flight Task Analysis

Sources of visual information available to a perceiver when viewing a natural scene while moving through it can be grouped into three general and independent classes: those contained in the pattern of disparities that exist between the two retinal images; those contained in the patterning of the continuous relative displacements of projected light on each retina that occur as the plane moves; and those contained in the perspective transformation of the light reflected from surface features as those features are projected on each retina. (I am excluding and ignoring several potential local sources of information, probably of little importance when looking at natural scenes, but perhaps used in the laboratory or other impoverished circumstances. Examples are accommodative and convergence corrections of the eyes as voluntary fixations shift from near to far or vice versa.) Each of these three classes provides information about the layout of space information that can fully specify the arrangements of space, such as surface orientation and scale, observer position and change in position relative to the surface, and location of all objects attached to the ground surface.

But the specification of the layout of space is quite different for each class of sources, with substantial differences in how the information is processed. For example, information produced by observer motion is available only when the observer in fact moves fast enough relative to his distance to the terrain surface so that the differences in displacement of edges on the retina are above threshold. There is little motion perspective information available to a hovering helicopter pilot, regardless of the nonuniformity of the terrain, nor to a bomber pilot at 50,000 feet even at supersonic speeds when the terrain is relatively flat. Further, binocular disparity information is available only when the observer's point of regard is close enough to the surfaces being looked at so as to be above stereoacuity thresholds. Since the two retinal images produced by a scene are virtually identical when the scene is more than several hundred meters distant, insufficient disparity is present to be detectable and processed. Hence, in theory, for most flying tasks, adding a second eye does not add much information beyond the increased field of view. This conclusion does not hold in theory for most helicopter flying tasks or for air-to-air refueling, for example, since for those tasks visual distances are well within stereoacuity limits so that disparities are above threshold. In practice, some low-level flight tasks even up to several hundred meters may benefit from binocular disparity information, but this is yet to be demonstrated.

While motion-produced visual information requires a moving observer and stereopsis requires the surfaces of the scene to be nearby, information from the perspective transformation of surface features is theoretically always available, even to a one-eye stationary observer. All that is needed are perceptible surface features such as textured surfaces and objects; contrasts in luminance or color between adjacent objects, between objects and the ground, or between different facets of each object; and of course contrasts produced by shadows or variation in surface orientation relative to the sources of illumination. The grain of these features differs, so at near distance the texture of the ground substance itself may be above threshold, whereas the same scene viewed from a great distance has a texture composed of the spacing of ground objects, such as trees or hills.

The above discussion of the kinds of visual information available from natural scenes suggests important restrictions when considering flight simulation for various flying tasks. For example, a stereoscopic display is probably important for helicopter pilot training, but is not likely to provide any useful visual information for any fixed-wing aircraft operation tasks (except perhaps air-to-air refueling) because all such tasks place the pilot at too great a distance from other visible surfaces or objects. Some careful work is needed to justify this conclusion, since it may turn out that there is sufficient stereoacuity available for some low-level flight tasks. The evidence presented by Regan in appendix C of stereomotion processing suggests the need for binocular displays to fully portray all of the information produced by observer motion; but for this, too, it needs to be demonstrated that stereomotion acuity is present even at the distance typically employed in low-level flight.

While a stereoscopic display in a helicopter simulator may be useful or even important, accurate display of surface features of helicopter flying is critical. When so much of the flying is at very low speeds, and often at no speed at all, movement produced changes are unavailable or uninformative. In the absence of a stereo display, the only information will come from the simulation of perspective transformations of light reflected surface features; and if the fidelity of those surface features is poor, if only a few features are present, or if their resolution is inadequate, simulator performance will necessarily be unrepresentative of actual flying performance.

This analysis suggests quite different visual specifications for simulation at low-level flight. The most useful source of visual information arises from observer-produced motion. Surface details are still important in the simulation, but since the pilot is capable of moving and maneuvering so rapidly, it is the motion information that is so predominant. Thus, improving fidelity of surface texture, especially of fine-grain texture, may not improve low-level flight simulation at all, whereas providing visual information that is easily processed for relative displacements over time across the retina would seem to be essential. Westra, Simon, Collyer, and Chambers (1981) reached the same conclusion based upon their experimental manipulation of a number of surface and motion variables for carrier landing flight performance, also a low-level flight task.

Given the focus of this report on low-level flight, the purpose of this brief paper is to examine some of the information sources that are produced by the pilot's movement through space. I especially want to single out one subclass of these sources, that based on optic flow patterns. This focus has potential interest because attending to such information sources may actually reduce rather than increase the demands on computing capacity, and because they are likely to be especially informative of the layout of visual space. Some suggestive experiments to be done on a wide-angle flight simulator are sketched at the end.

A Division of Labor--Central and Peripheral Vision

We tend to look directly at the important sources of information in visual scenes because doing so images that information on the central high-resolving part of the retina. But the fovea can cover only about one-ten-thousandth of the area of a visual scene at any one moment, the rest falling on the peripheral retina of lower resolving power. While we have learned a great deal about information processing in central vision, much less is known about how peripheral stimulation is impaired when only central vision is permitted. Particularly, it seems likely that tasks involving orientation in visual space and especially locomotion through visual space depend upon information from the full scene information available only to the peripheral retina.[1]

While the above comments are couched in a somewhat intuitive form, several recent theoretical developments have helped formalize the intuitions. The most important of these is the notion that visual functioning may be served by two somewhat independent visual processing systems, one concerned with object recognition and identification--the "what" of perceptual experience; and the other concerned with spatial localization and orientation--the "where" question (e.g., Schneider, 1969; Held, 1970). Such a division of functioning coincides closely with the differential sensitivities of the central versus peripheral retina, and with the differential degree of optical resolution over these areas. It also relates to differential loss of function that occurs with disturbance to different brain structures (e.g., Poppel et al., 1973), suggesting some independence to processing of what and where information. Finally, it has been shown (e.g., Leibowitz et al., 1979) that while questions of identification are critically dependent upon both stimulus energy and the optical quality of the retinal image, spatial orientation processing is relatively independent of energy and image of quality as long as the scene is visible at all.

A substantial part of the task facing a pilot during low-level flight concerns having precise visual information about the location of the ground in relation to the plane as it changes from moment to moment. From the distinction presented above, it would seem likely that such information is imaged over the entire retinal surface and not concentrated only over the fovea, and is not dependent upon either high optical resolution or intense energy. Both of these conclusions, if true, have obvious implications for the design of low-level flight simulation displays.

Spatial Orientation Information Available to a Moving Perceiver

Perspective geometry provides a description of changes in the projection of light to an observer reflected from objects and surfaces as the observer moves (see Haber, 1979, for a brief review). The simplest circumstance, called motion parallax, is when there are only two points in the scene reflecting light: in such cases, the light reflected from the two points shifts position on the retina in proportion to their relative distance from the observer. Thus, the amount of relative change over time on the retina can provide information about relative distance from the observer--information that is not available to a stationary observer. While motion parallax is a simple circumstance, and is considered one of the basic monocular cues to depth, much more interest has been focused on its generalized extension, in which all of the projected points of light move relative to one another as an observer moves through a visual scene. Gibson (1950) referred to this as motion perspective and emphasized that the information covers the entire retinal projection surface and is not restricted to merely a few points of light in relative motion. Thus, when an observer moves, a continuous gradient of perspective is projected onto the retina, with the rate of change at each point providing a mapping of the contours of the terrain being traversed. Gordon (1965) and more recently Koenderink and van Doorn (1975, 1976) have provided a detailed breakdown of the geometrical information available at a projection surface to a moving observer. Nakayama and Loomis (1974) have carried this work further by suggesting the kinds of neural mechanisms that could encode this gradient--neural mechanisms of the same order as those that account for binocular disparity encodings. Ullman (1979) has incorporated these features with a more general model of motion perception, and Lee and Lishman (1977) have reported some psychophysical experiments on the visual control of locomotion using motion perspective information.

---

[1] Empirical investigations have not shown much effect of display field of view on tasks such as landing. In contrast, with some tasks, such as aerobatic maneuvers, field of view has been found to affect performance (see Hennessy et al., 1980).

One aspect of motion perspective discussed in detail by Gibson and others since refers to optic flow information. When looking ahead, light reflected from the point in the scene toward which the observer is moving remains centered on the retina, only expanding in size as it gets closer. All other reflected points flow across the retina toward the periphery, with a relative rate of flow proportional to the distance of the reflecting surface to the observer. In this way, the flow pattern represents the layout of the scene, with the aiming point of the moving observer being indicated by a zero flow vector. Since observers usually look at that toward which they move, this means that information about the direction of observer motion is available to central vision. But the flowing part of the flow pattern covers the entire retina, and not only can specify direction and velocity of the observer, but more important, the location and irregularities of the terrain. None of this specification need be projected to central vision. It is likely that such optic flow patterns are the most important source of information about general terrain characteristics and the observer's orientation and location over that terrain. Because optic flow does not depend upon central vision, it may be handled entirely by the "where" system, and if so, flow can be represented by a simulator display with low-resolution, low-intensity elements.

I have three further notes before suggesting some experiments. When an observer moves relative to the terrain, a system with high temporal resolution is capable of representing each projected point of light as a unique point. The human visual system, however, has a relatively low temporal sensitivity, so that a moving point of light is perceived as a streak or blur line (Smith, 1969). Much of the optic flow has to be streaks, especially in the periphery of the retina. Harrington et al. (1980) have shown that perceivers are able to judge orientation quite accurately from optic flow that was entirely blurred, even out of 75 degrees from the fovea.

My second note concerns the effects of psychological or physiological stress on the processing of "what" and "where" information, and especially on the relative weights placed on central and periphery information. Mackworth (1965, 1976) reported studies that suggested that under stress or high information loads, identification processing becomes tunneled, so that information picked up peripherally is less adequately processed. His studies did not investigate location or orientation information processing, so it is not clear whether stress produces tunnel vision for "where" as well as "what" information; though it is possible that the periphery does not suffer any functional loss for processing of optic flow information. It is important to know how the details contained in the flow are processed: (a) which provide information about the objects on the terrain, as compared to how the flow itself is processed, and (b) which specify the orientation of the terrain.

My third point is a more general one. We as yet do not know all of the sources of visual information that are available, and even of those, we do not know which ones are used in what contexts. Thus, one of the goals of research programs on space perception, even one focused on simulation training, has to be to examine the psychophysical relationships between sources of information and subsequent perceptual performance. This need is powerfully illustrated by the recent work of Owen (e.g., Owen et al., 1981a,b), who has shown that it matters greatly whether the visual variables are defined in terms of visual information specifying environmental surfaces or in terms of specifying the relations of the perceiver to those surfaces. In Owen's experiments, it turns out that the latter specifications are the ones which predict performance, suggesting that the psychophysical relationships include the perceiver in the equation. The important point is that there are many ways to define and specify each of many different optical variables, not all of which are equivalent. Only by psychophysical research can we determine which variables have what properties. It cannot be done simply by a geometric analysis in an arm chair.

Some Suggested Experiments

With these questions and assumptions in mind, I have sketched out some research problems that should be addressed and, in some cases, have provided more details as to procedure. While my focus is primarily on the use of visual information that falls on the peripheral retina during low-level flight and therefore in how to present such information in simulation of low-level flight, expanding our knowledge in this area will correct deficits in current theories of visual perception and could be of great practical value in designing the arrangements of visual displays such as instrument panels, monitors, and warning devices; and in designing general visual simulation equipment and the programs for displaying simulated scenes, not only for low-level flight but for tasks like driver training and for improved methods of training target detection.

What is needed are studies directed at demonstrating the aspects of the visual display actually used in various locomotion tasks. Since we need to know this within the context of low-level flight simulation, such studies require the use of a wide field-of-view simulator programmed for low-level flight. For some of the experiments sketched below, an additional closed loop control is needed, so that the monitored direction of gaze of the subject's eyes is used to vary the content of the display. Hence, when looking straight ahead, the details of the optic flow pattern seen through the side windows would be of low resolution, but if the pilot turned his head to look to the side, the resolution would sharpen to correspond to the improved acuity of central vision. Such on-line monitoring of gaze direction and closed loop control of display resolution is not necessary for all of the experiments, but it is critical for some that should be done.

The general procedure involves pilot-subjects (perhaps including subjects with little flight experience) flying in a wide-view simulator on various low-level flight tasks, such as terrain avoidance while maintaining a limited altitude, reconnaisance and target acquisition, or more specific tasks such as flying a prescribed course or maintaining a fixed altitude above the ground. Given these types of tasks, various stimulus changes could be evaluated as to their effect on flight performance.

One set of studies involving stimulus manipulation might provide a mislocation of the zero point of the optic flow vector, so that the plane's flight path was not always aimed at the zero point, even though the rest of the flow pattern was correct. If pilots use this information, substantial disruption in flight performance (and perhaps disorientation and discomfort) should occur. A related manipulation might occlude the zero point in the flow pattern so the pilot could see it, though he could see all else in the scene. Further, along the same lines, we could manipulate how far ahead of the plane optic flow information is useful in relation to velocity. When flying at high speed, pilots gain little useful information directly in front of the plane. In effect, the pilot has to focus well ahead. This tunneling of vision produces more reliance on optic flow because less detailed pattern information can be picked up.

A different set of studies should look at the content of the flow pattern itself.

Conceivably the flow is processed entirely in the peripheral retina, and conceivably it is handled by neural circuits concerned only with motion and not with pattern or edges. In that case, it would be less important how flow is represented in the display, and considerably lower resolution could be used without loss of performance. Again, the same sorts of tasks can be used to evaluate performance as a function of the content and the resolution of the flow.

A third set of studies could look at an interaction of flow patterning with detection of specific targets as the flow passes. If flow is merely relative movement, how do we also detect the presence of a sought-after target object? When looking straight ahead at the zero vector point, what are the minimal size, contrast, color, and context characteristics of objects displayed in the optic flow necessary for detection as they stream past the observer? Presumably, a sought-after or surprising object, once detected, causes an eye movement toward it away from the zero point, but what does it take to produce detection and reorientation?

These studies constitute only a small subset of possible ones that could be done on flow and peripheral information pickup. But they are a start, and they can be easily expanded once the programs and procedures are set up. None of these studies are ground-breaking in a theoretical sense, though they will allow us to test some of our hallowed theories. But they provide needed data for design of flight simulation displays, as well as general visual training procedures.

REFERENCES

Gibson, J. J.
1950 *The Perception of the Visual World*. Boston: Houghton Mifflin.

Gordon, D. A.
1965 Static and dynamic visual fields in human space perception. *Journal of the Optical Society of America* 55:1296-1303.

Haber, R. N.
1979 Perception of visual space in scenes and pictures. Pp. 8-51 in L. D. Harman, ed., *Interrelationships of the Communicative Senses*. Washington, D.C.: National Science Foundation.

Harrington, T. L., Harrington, M. K., Wilkins, C. A., and Koh, Y. O.
1980 Visual orientation by motion-produced blur patterns: Detection. *Perception and Psychophysics* 28:293-305.

Held, R.
1970 Two modes of processing spatially distributed visual stimulation. Pp. 317-324 in F. O. Schmidt, ed., *The Neurosciences: Second Study Program*. New York: Rockefeller University Press.

Hennessy, R. T., Sullivan, D. J., and Cooles, H. D.
1980 *Critical Research Issues and Visual System Requirements for a V/STOL Training Research Simulator*. Technical Report NAVTRAEQUIPCEN 78-C-0076-1. Orlando, Fla.: Naval Training Equipment Center.

Koenderink, J. J., and van Doorn, A. J.
1975 Invariant properties of the motion parallax field due to the movement of rigid bodies relative to an observer. *Optica Acta* 22:773-791.

Koenderink, J. J., and van Doorn, A. J.
1976 Local structure of movement parallax of the plane. Journal of the Optical Society of America 66:717-723.

Lee, D., and Lishman, R.
1977 Visual control of locomotion. Scandinavian Journal of Psychology 18:224-230.

Leibowitz, H. W., Rodemer, C. S., and Dichgans, J.
1979 The independence of dynamic spatial orientation from luminance and refractive error. Perception and Psychophysics 25:75-79.

Mackworth, N. H.
1965 Visual noise causes tunnel vision. Psychonomics Science 3:67-68.

Mackworth, N. H.
1976 Stimulus density limits the useful field of view. Pp. 307-322 in R. A. Monty and J. W. Senders, eds., Eye Movements and Psychological Processes. Hillsdale, N.J.: Lawrence Erlbaum Associates.

Nakayama, K., and Loomis, J. M.
1974 Optical velocity patterns, velocity-sensitive neurons, and space perception: A hypothesis. Perception 3:68-80.

Owen, D. H., Warren, R., Jensen, R. S., Mangold, S. J., and Hettinger, L. O.
1981a Optical information for detecting loss in one's own forward speed. Acta Psychologica (in press).

Owen, D. H., Jensen, R. S., Alexander, G., Warren, R., Mangold, S. J., and Hettinger, L. L.
1981b Transformation realism: An interactive evaluation of optical information necessary for the visual simulation of flight. Pp. 385-400 in Proceedings of the Image Generation/Display Conference II. Williams Air Force Base, Ariz.: Air Force Human Resources Laboratory. AFHRL-TR-81-48, AD-A110 226.

Poppel, E., Held, R., and Frost, D.
1973 Residual vision after brain wounds involving the central visual pathways in man. Nature (London) 243:295-296.

Schneider, G. E.
1969 Two visual systems. Science 163:895-902.

Smith, V.
1969 Scotopic and photopic functions for visual band movement. Vision Research 9:293-317.

Ullman, S.
1979 The interpretation of visual motion. Cambridge, Mass.: MIT Press.

Westra, D.P., Simon, C. W., Collyer, S. C., Chambers, W.S., and Nelson, B.
1981 Investigation of simulation design features for the carrier landing task. Technical Report NAVTRAEQUIPCEN 78-C-0060-7. Orlando, Fla.: Naval Training Equipment Center.

APPENDIX E

DISPLAY DESIGN VARIABLES PERTINENT TO LOW-LEVEL FLIGHT SIMULATION

Harry L. Snyder

Introduction

The main body and other appendixes of this report contain analyses of known difficulties and problems in the visual simulation image content of low-level flight. Issues of pertinent visual scene parameters are addressed, the importance of many visual parameters to pilot training and performance is noted, and suggested experimental activities to define better the information content of the visual simulation are described. This paper, on the other hand, takes a different approach, one complementary to the others. It does not address the requirements for information content of the visual scene, but rather addresses the requirements for the display generation equipment, in visually relevant terms.

This appendix therefore serves two important purposes. First, it notes the pertinent hardware/software design requirements for visually compatible information presentation _if_ the information is adequately defined and described in usable parametric terms. Second, it addresses some of the technologically limiting characteristics of visual displays, thereby noting the limits of the visual information which _can_ be presented.

In the final analysis, if visual information presentation requirements are found, through analysis or empirical experimentation, to exceed current display generation technology, then research and development requirements for simulation technology can be defined in a useful manner. On the other hand, if information requirements are far less than those of which the simulation equipment is capable, then potential cost savings and complexity reduction can be achieved. In either event, it is important to understand the relationships between visually pertinent variables and measurable characteristics of the simulation equipment.

Finally, this appendix addresses briefly the issue of measurement and verification of the visual display in photometric and geometric ways directly pertinent to the visual characteristics of importance. Display technology has advanced rapidly, at a more rapid rate than the metrology needed to define and refine its image-producing specifications. While some work has been done recently to recommend those techniques and criteria for adequate and accurate display quantification, universal application of these techniques is far from prevalent. Thus, the relationships between some of these measurement techniques and vision-related variables are summarized briefly.

Display Variables Critical to Visual Simulation

This section describes those display variables considered to be critical to the presentation of visual information in low-level flight. The format, density, and content of the information to be displayed is described elsewhere in this report. This section assumes the need for the visually compatible presentation of various types of information, and suggests minimal relationships which must hold for adequate presentation of that information. Wherever possible, known data and experimental results will be referenced.

Display Field of View

The field of view (FOV) requirements for visual simulation have been amply shown to be task dependent. Take-off and landing tasks appear to require only a limited FOV, on the order of 50 to 60 degrees or less. On the other hand, air-to-air combat, and by analogy low-level flight, requires visual scanning by the pilot and foveal acquisition of high spatial frequency information from various parts of the visual field typically available through the cockpit canopy. Studies have included parametric investigation of FOVs as large as 180 degrees. Although statistical results have been limited, it appears that the larger (e.g., greater than 150 degrees) FOV is needed for reconnaissance, low-level navigation, and target acquisition activities, and perhaps for terrain avoidance.

Translation of this requirement into realistic hardware presents several problems. First, a single image, from a single projection device, to cover at least 150 degrees is limited to either low-resolution electronic imaging or higher-resolution film-projection devices. For example, the JTF-2 visual simulator had a field of view of 160 by 60 degrees, used a 70 mm film format, and had a limiting (high-contrast) resolution on the order of 3 arc minutes in the center of the FOV. Single CRT projection devices will have a maximum resolution on the order of 1,200 picture elements (pixels) per display width, and therefore no better than 8 arc minutes limiting resolution. For this reason, the typical approach has been toward butted images from several CRTs, with the attendant problem of edge discontinuities or image gaps due to registration errors between adjacent images. (The adjacency or segmentation problem is addressed below.) High-resolution elements (e.g., targets) can also be inserted from a second projector, and high-resolution "windows" in the total field can be slaved to the pilot's head position to improve resolution in a part of the display.

At the present time, the designer has a complex trade-off to make between FOV and resolution, increases in one generally causing decreases in the other. Since no quantitative data appear to exist on the effects of FOV on low-level flight control or navigation, it would appear that parametric research dedicated toward this determination is extremely important. Preceding such experimentation, one should conduct thorough analyses of the task and information requirements of the pilot in the mission phases of interest. As Semple et al. (1980: 79-80) pointed out,

> the value of a wide FOV may not have been apparent in the studies reviewed because the tasks did not specifically demand use of more than a central FOV. For example, air to air combat obviously requires a wide FOV. Therefore the decision on whether a wide or narrow FOV is necessary for training purposes must take into account specific task requirements and not be based solely on possible unwarranted generalizations from research results . . . from a limited number of flying tasks.

The low-level navigation and target acquisition task is not among those which has been parametrically investigated, and therefore requires careful research on FOV trade-offs.

Dynamic (Luminance) Range

Projection systems have a finite amount of luminous energy that can be distributed across the FOV. Increases in the FOV, obtained optically, will result in proportionately lower luminance levels, assuming screen gains and optical efficiency to be approximately constant. The only exception to this generalization is in the use of multiple CRTs or other segmented means of controlling the image luminance per screen segment by increasing the number of sources rather than spreading the energy from a single source over a wider FOV.

While the observer will visually adapt to the mean luminance level of the entire display, assuming scanning behavior such as to fixate foveally the overall field, reductions in luminance range will necessarily reduce the number of discriminable levels of luminance. More importantly, the contrast sensitivity of the observer will decrease with decreases in luminance, thereby further reducing the observer's discrimination of luminance differences and decreasing his cutoff spatial frequency, resulting in a loss of effective acuity.

It would appear that the attenuation of luminance range is important in that the contrast sensitivity function (CSF) shift is critical to the perception of small details, and perhaps to the perception of depth relationships. Thus, luminance requirements can be stated only once we know the requirements for spatial information presentation (resolution) of the image. Experiments to determine the resolution requirements are considered important for this as well as other reasons.

Existing research results permit us to recommend a limiting resolution of no more than 3 arc minutes for such activities as target acquisition in an air-to-ground search (Humes and

Bauerschmidt, 1968). The author knows of no comparable data for performance effects attributable to resolution in tasks such as low-level navigation and terrain following. Again, a task analysis leading to information requirements might help. Other experimental techniques based upon scene spatial filtering and observer static target and object recognition might also be helpful. Simplified closed-loop flight control simulations with varying image resolution may also serve to provide useful information on the requirements for display resolution and therefore dynamic range.

MTF

The preceding discussion related resolution requirements to dynamic range. A more useful measure, which combines both luminance range and resolution is the modulation transfer function, or MTF. In this approach, the output modulation (or contrast) of the display is determined for all spatial frequencies, assuming a constant input modulation (M). Thus, the MTF specifies the modulation the display system is capable of delivering at any spatial frequency, assuming a unity modulation input. The engineering convention of describing "shades of gray" as $2^{0.5}$ increments in luminance can be converted to equivalent modulation by the following formula:

$$N \text{ (shades of gray)} = 1 + \frac{\log ((1+M)/(1-M))}{\log 2^{0.5}} \qquad (1)$$

In recent years it has become recognized that the specification of an MTF is more meaningful and pertinent than the specification of merely a limiting resolution. The "limiting resolution" of an imaging system is, in actuality, the spatial frequency at which the MTF of the display system crosses the CSF of the observer (Snyder, 1973). More importantly, the MTF also describes the ability of the display system to render high contrast inputs faithfully at spatial frequencies below the limiting resolution. As such, the MTF describes the ability of the imaging system to faithfully reproduce input contrasts at all usable spatial frequencies of the system, whereas the limiting resolution specifies only the spatial frequency at which the system ceases to provide information to the observer, a measure of little utility.

Little research has been conducted to relate observer performance to MTF variations for many tasks, although data do exist for tasks such as face recognition and air-to-ground target acquisition (Gutmann et al., 1979; Snyder, 1974; Snyder et al., 1974). Assuming the low-level navigation and flight control tasks to be reasonably related to air-to-ground target acquisition, then it would appear that a display system with an MTF at least equal to that shown in figure E-1 would be desirable. Unfortunately, as figure E-1 also illustrates, current technology is far from this capability. Research of a more directly applicable nature, using flight control rather than target acquisition as the dependent measure, is clearly indicated.

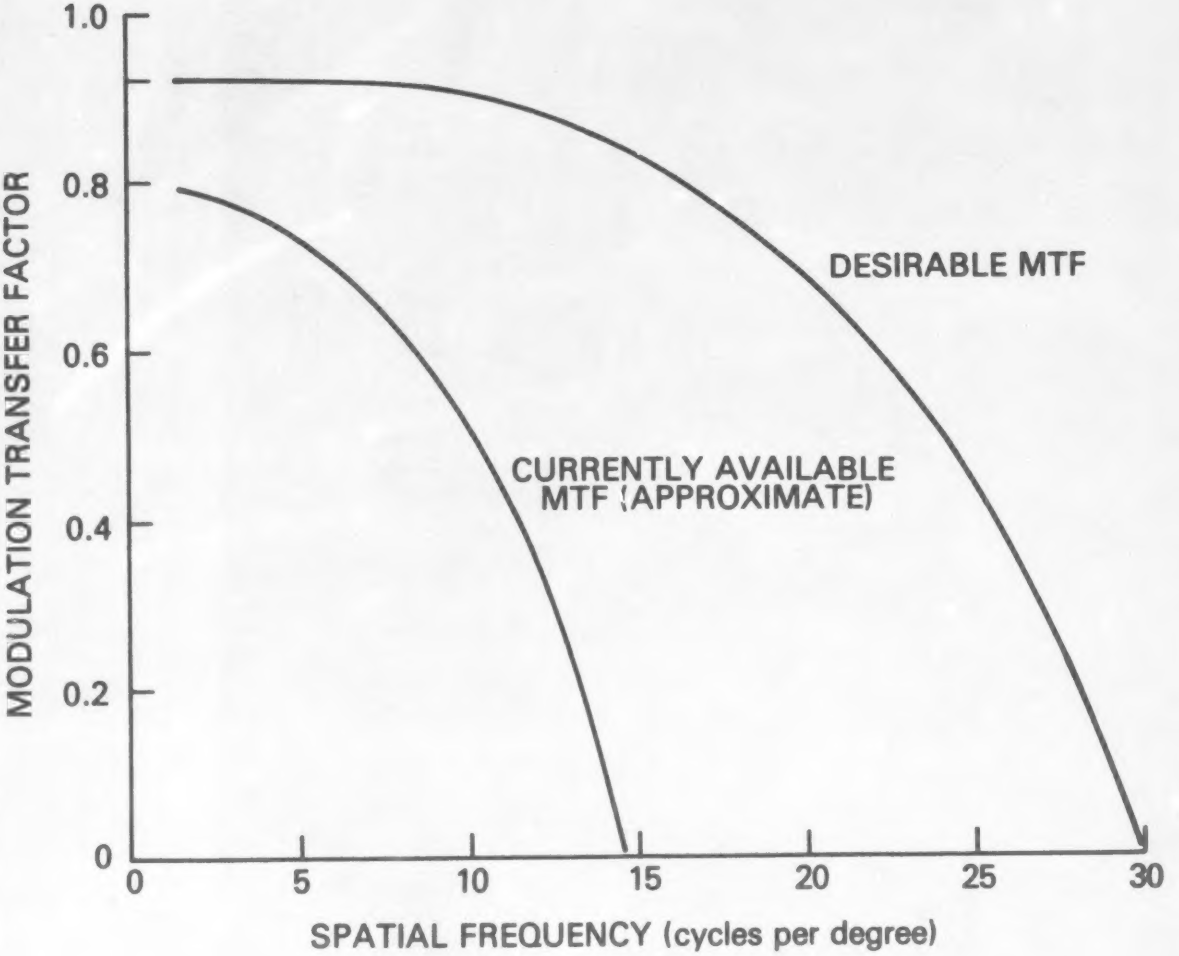


FIGURE E-1 Recommended minimal display system MTF for low-altitude simulation.

Refresh Rate

Computer-generated displays are of finite bandwidth, and this bandwidth must be allocated between the number of displayed picture elements (pixels) and the refresh rate. It is often feasible to reduce the refresh rate by using longer persistence display surfaces, thereby achieving greater spatial resolution. However, with dynamic motion typical of low-altitude flight, longer persistence displays would be subject to blur or streaming. Thus, a careful trade-off is needed between spatial resolution and temporal resolution (refresh rate). This trade-off also exists in film projection systems, where the shutter angle of the cine projector, in conjunction with its frame rate, must be selected to avoid image jump or strobing.

The refresh rate is set by both flicker fusion thresholds and the image motion rate. As image motion increases, typically at the bottom center portion of the display as a limiting condition, inadequate refresh rates yield image breakup or a perception of image strobing (Snyder et al., 1966). Solutions to the strobing problem are to increase the refresh rate, permit blurring, or decrease the angular rate of the image by decreasing the look-down angle. These trade-offs are quantitative and established in terms of the strobing phenomenon (Snyder et al., 1966); further, the minimum refresh rate to avoid flicker can be specified by a Fourier analysis of the temporal luminance distribution, which includes the refresh rate convolved with the persistence of the display system (Snyder, 1980). Reductions in refresh rate are helpful in bandwidth allocation. A 60-Hz rate, while standard, may not be needed.

In general, then, the needed specification for refresh rate depends largely upon knowledge of the field of view, the maximum simulated aircraft velocity and altitude (to obtain V/H), and the number of pixels in the display requiring refresh every frame rate. No research seems warranted on this parameter except for verification studies once the FOV and resolution/MTF requirements are set.

Information Update Rate

The display refresh rate is established to avoid flicker, and must also be compatible with the need to eliminate strobing, as described above. At the same time, there is often a need to refresh the display to change the state of information depicted on the display. Some information rate updates are required by the strobing problem, but others are needed to achieve sufficiently accurate information placement in the field, even though strobing would not occur with a lower update rate. Careful analysis of the rate of movement of displayed elements, along with the placement accuracy required, both spatially and temporally, is needed for the low-altitude flight regime. This analysis, in conjunction with the information requirements work described elsewhere, should produce information update rates compatible with the pilot's visual needs.

Virtual Versus Real Image

Two approaches are popular in visual flight simulation. In one, the image is created on a display surface such as a CRT and viewed through a collimating lens to produce an image at optical infinity. With this approach, the pilot can move his head in translation without relative image motion; in addition, the accommodation of the eye is comparable to that required in actual flight to view the real world. In this mode, the pilot must shift accommodation realistically between the visual scene of the projected display and the in-cockpit information, creating thereby appropriate visual loading and accommodation time lags.

The second approach largely ignores this problem of accommodation shift between in-cockpit tasks and optical infinity, and projects a real image on a (typically) spherical screen in front of the cockpit. The radius of curvature of such screens is usually on the order of 6 to 15 feet, thus requiring some accommodation shift between the cockpit displays and the projected real world; however, the advantages of this type of simulation are freedom of distortion and separation introduced by the segmented collimating optics or separate display surface.

It must be realized that noncollimated display of scene information that would normally exist at optical infinity may lead to misperception of the size of objects (Leibowitz et al., 1972; Roscoe, 1951). In addition, movement of the pilot's head with respect to noncollimated images may result in misjudged distance perception (Gogel and Teitz, 1973), although it is likely that an image distance in excess of 10 feet will minimize this effect.

Whether the collimated display has any real advantage, particularly for training, over the noncollimated, real-image display is an empirical question. Certainly, if the noncollimated display can avoid the image segmentation typical of many multiple-image, pancake-window optics used in collimated, wide-FOV displays, then the advantage may well rest with the noncollimated display. It would appear, as suggested by Semple et al. (1980), that the decision may well be a matter of economics rather than performance, although this writer recommends a direct experimental comparison between the two, using the same tasks and imagery, to determine if any significant difference exists.

Image Geometric Linearity

Perfectly collimated images will produce geometrically linear displays if the display generator is geometrically perfect. All too typically, however, the edges of the display suffer from slight noncollimation, exhibiting a small amount of "swim" in the corners. This can be distracting to the observer, especially if the image corners are butted with other images. The same problem can exist in a noncollimated image if sufficient care is not taken with the anamorphic optics (among others) to correct for screen curvature, center of curvature, etc. (The subject's head and the projector cannot both occupy the center of curvature position!)

A critical question is the extent to which noncollimation or geometric nonlinearity may cause performance or training differences by pilots. There are no data on the effects of display nonlinearity on even simple tasks such as object recognition or text reading, let alone on pilot performance during low altitude flight (Snyder, 1980). Such data are needed, but are probably not as critically related to pilot performance or training efficiency as are other variables discussed in this appendix.

Image Segmentation

The problem of alignment and separation of multiple-image displays was discussed in a literature review and analysis report by Kraft et al. (1980), who recommended experimental investigation of the segmentation and alignment problem. In a subsequent investigation, Kraft and Anderson (1980) determined the ability of U.S. Air Force pilots to detect joint-width differences, misalignments, and rotations among image portions. This study was conducted with static, daylight scenes, and the subjects were not required to perform any complex, closed-loop task by reference to the scenes.

Kraft and Anderson (1980) found that joint widths of 15 arc minutes or more masked vertical displacement errors up to 1.4 arc minutes. They also found that joint widths of less than 15 arc minutes led to more critical tolerances of rotational errors.

Whether these acute judgments by their subjects would be upheld in more complex tasks, such as low-altitude navigation and terrain following, is an empirical question. It would seem doubtful that the heavily loaded pilot would be as sensitive to such small errors in the visual display under such conditions. Further, it may well be the case that detection of small image segmentation and alignment errors may have no impact on the training utility of the simulator. At the present time, no useful data exist on this point.

Jitter

Many CRT displays exhibit substantial vertical jitter, a field-to-field or frame-to-frame vertical movement in the image caused by instability of the vertical deflection circuitry. Unfortunately, such jitter is often greater than the spot size of the display, thereby causing a reduced vertical resolution or a high-frequency roll-off of the MTF in excess of what spot-size limitations would dictate.

It is quite feasible that this jitter, while not detectable directly, causes many of the visual fatigue symptoms experienced by users of visual display units (usually CRTs) in office environments. If so, it is also reasonable to think that jitter may cause visual fatigue (tiredness, headaches, etc.) in the simulator pilot after substantial time in the simulator.

While jitter is measurable, it is often not carefully controlled in CRT deflection design. Thus, many solid state, flat panel displays are judged to be better in image quality by some observers due to their lack of jitter.

No experimental data currently exist on the relationship between jitter amplitude and frequency and objective performance measures of observers. Further, no data exist on the effect of jitter variables on subjective reports of visual fatigue, although anecdotal stories have been recorded (Snyder, 1980). A parametric study of the effect of jitter on visual performance is clearly warranted. In the absence of such experimentation, careful measurement and control of jitter should be of prime concern in the design of any visual simulation system.

Color

The use of color in visual simulation for training has been investigated in at least two studies. Chase (1970) investigated the effect of color on training for approaches and landings, and obtained small but positive differences in favor of color. On the other hand, Woodruff (1979) found no differences in either learning rates or final performance using color versus black-and-white TV displays. Similar results have been found in air-to-ground target acquisition tasks. Snyder, Greening, and Calhoun (1964) found no differences in target acquisition for color versus black-and-white in a film projection simulation, while Fowler and Jones (1972) found no differences in an air-to-ground TV simulation.

It should be noted that the atmospheric attenuation of color is quite rapid, with very little color remaining beyond a few miles of clear atmosphere (Middleton, 1952). With the exception of simulation of cultural objects, such as landing and runway/taxiway lights which are intrinsically color coded, there appears to be little need for color simulation, although pilots report that a simulator display with color is very pleasing (Semple et al., 1980).

It appears that parametric experimentation on the requirements for color in low-altitude flight is urgently needed, not because of the aesthetics involved, but rather because of the economics. Image generation in color is usually more complex and expensive, as is the design of optics that avoid chromatic distortion. Further, the possibility of false depth perception, due to chromostereopsis, must be avoided. If color does not aid in either performance or transfer of training, then there appears to be no noncosmetic requirement for such. On the other hand, color enhancement might provide improved training efficiency, but this determination is yet to be made.

Stereo Imaging

The need for stereoscopic display for flight simulation has been considered by many, but never implemented or evaluated experimentally. On the negative side, one can argue that most of the visual information pertinent to the flight environment occurs at distances on the order of several hundred feet or more, and that no binocular cues (e.g., convergence, retinal disparity) or accommodation cues exist at that optical distance. Conversely, the existence of stereo channels (see appendix C) creates some concern for potential distortion of the visual scene without presentation of stereoscopic information which might be above threshold for these channels.

While this issue cannot be adequately resolved at this time due to lack of a complete understanding of the relationship between stereo channels and low-altitude flight performance, the issue certainly warrants further analysis and perhaps experimentation along the lines presented in appendix C.

Measurement Issues in Display Variables

In the past, specifications for visual simulation systems have been incomplete in that they have not contained parameters and measurement procedures pertinent to the observer's visual requirements. For example, specification of video bandwidth, line rate, and maximum video voltage may define the limiting performance of the display, but they do not define the luminance range, the MTF, the actual limiting resolution, the line pairing or interlace accuracy, or other vision-related characteristics. What is needed, of course, is a set of measurable displayed image variables, the required levels of which are minimum for adequate visual performance of the pilot. In addition, there must be specified the operational procedures by which quality control of these characteristics is maintained in both acceptance testing and subsequent maintenance. To date, only a few military operational systems have been purchased and maintained under these procedures, and no simulator systems have had to meet stringent and pertinent design requirements.

The following paragraphs describe but four of these measurement categories. While others exist, it is the proper province of the system designer to specify both the critical design parameters and the procedures by which those parameters will be measured and maintained. The following is therefore suggestive, and not definitive.

Radiometric/Photometric Control

Many CRT and flat panel displays are stated to provide certain levels of luminance (albeit often called "brightness") under maximum signal conditions. Some contain specified luminance levels for zero voltage input. Unfortunately, two problems exist in these specifications. First, the maximum luminance level is not achieved in a CRT without some loss of resolution due to spot bloom; second, the "black" level is never at zero luminance due to scattering, faceplate reflectance, and other conditions. Thus, the obtained maximum modulation is always less than unity, and the true amount of achievable modulation is never stated.

While the problem is somewhat different for a solid state display, the maximum luminance is often dependent on the number of pixels turned "on" and may also vary with "half-select" voltage characteristics of the device, an issue rarely addressed in the performance specifications of the device.

Recent research has resulted in recommendations for radiometric scanning of the display device under known input conditions. A scanning monochromator is used to obtain radiant energy per unit wavelength, which is then converted to photometric power and ultimately to luminance if that is of interest to the user. Accuracies are obtainable of better than 1 percent, and dominant wavelength can be measured to within 2 nanometers. CIE coordinates can likewise be calculated from the radiometric scans to within .002 in x and y (Farley and Gutmann, 1980).

These measurement techniques are particularly valuable in color research and in chromatic control of the display when constant luminance or constant brightness is needed. Further, computerized scanning and calibration is achievable on a scheduled basis, using self-calibrating radiometric equipment and programmed inputs to the display device. Outputs from periodic calibration can be used to define requirements for adjustment, maintenance, or replacement of display components. In particular, since the luminance and chromatic drift of many CRTs is as much as 10 percent in less than one hour, periodic measurement is needed during research activities and perhaps during simulation tests.

Measuring MTF

The static MTF of a display can most easily be measured with either a square-wave or a sine-wave grating inputted to the display, and the display surface scanned microphotometrically or microradiometrically with a slit scanning microscope. The scan, taken over several cycles, is then Fourier analyzed to determine (1) the modulation at the fundamental frequency, (2) the spatial frequency of the fundamental, to check for magnification errors, and (3) any harmonic distortion as evidenced by inappropriate luminous power in higher harmonics. Since digitally addressed displays cannot reliably and accurately reproduce a sine wave at high spatial frequencies, the most convenient technique is to input a square wave, followed by correction by a factor of 4/pi to obtain the equivalent sine-wave modulation, assuming system linearity.

Systematic inputs of varying spatial frequencies, followed by plotting of the modulation in the Fourier spatial fundamental, yields the MTF curve. This procedure should be done in both the vertical and the horizontal display dimensions to measure both MTSs, as most displays are anisotropic. In addition, when a raster scan is used, the luminous power in the raster can be determined in this fashion with a constant (gray) image input signal. If any line pairing exists in the raster, the Fourier line spectrum will show a reduced modulation at the raster fundamental frequency and more modulation at higher order harmonics. These and other measurement techniques are described in Snyder et al. (1974) and in Snyder and Maddox (1978). Dynamic MTFs are more complex and are critical to this problem, but need not be discussed here.

Measuring Jitter

The measurement of jitter requires careful measurement in the temporal rather than in the spatial domain. Jitter is most easily measured by placing the object plane aperture of the microphotometer at the edge of a raster or image element line, and then sampling the radiance or luminance output during successive refresh cycles. Variation of this output, for a constant input, denotes jitter (or luminous noise). Zero-lag sampling can be most easily obtained by recording directly from the dynode of a photomultiplier tube photometer and presenting successive output levels on a storage oscilloscope. Measurements in rms luminance can be made directly from the oscilloscope image if the photomultiplier tube output has been calibrated. Details of this technique are described in Snyder et al. (1979).

Dynamic Characteristics

CRT displays are subject to several forms of dynamic changes over time. Noted above were jitter, luminance instability, and chromatic instability. These changes are largely due to fluctuations in line voltage, heating of electronic elements within the display, and fluctuations in driving signals. Other image-related, dynamic characteristics of concern include chrominance changes due to misconvergence of the color electron guns with the shadow mask, long-term drifts in luminance and therefore MTF, and long-term changes in spot size, which also influence the MTF and limiting resolution.

Each of these dynamic changes can be measured with standardized spatial or temporal microphotometric or microradiometric measurements, usually of the form described above. What is critical is that they are measured and are not simply assumed to be stable for the useful duration of the system. Since such degradations are gradual (often called "graceful"), they tend to go unnoticed, all the time potentially degrading performance of the user until total failure occurs.

Measurement and drift are especially critical for those parameters shown to be sensitively related to pilot performance. During research studies to determine display requirements, in particular, these measurements should be made systematically and periodically, recorded, and related to any trends in subject performance. In an operational training environment, such measurements would similarly be made, recorded, and related to long-term trends in training effectiveness. To the extent that one must be careful in specifying optimum levels of display system parameters, one must also be careful to retain those levels during operational usage.

Issues Warranting Research Consideration

Many variables relating to image content may require careful research to yield flight simulation displays adequate for efficient low-level flight training. However, specification of the image content variables will be of little value if the displayed image is inadequate to present the content with acceptable fidelity, consistency, and quality. For these reasons, the following variables may be critical in display specification/design and warrant experimental or analytical investigation as to their impact on performance and training transfer for low-level flight:

1. Field of View: The relationship between FOV (vertical and horizontal) and pilot performance for training effectiveness in low-altitude simulated flight must be determined, as this is critical to the design of a variety of display system characteristics.
2. MTF: The effect of system MTF on pilot performance for training effectiveness must be similarly measured. Increases in MTF are difficult and expensive, and overspecification is unfortunately possible, though greatly uneconomical.
3. Virtual versus Real Image: A direct comparison of collimated with noncollimated images should be made, using pilot training performance as well as subjective ratings as criterion measures. Size, complexity, and cost considerations relate directly to this evaluation.
4. Jitter: Some jitter (or other dynamic sources of image quality loss) will always remain in CRT-based systems. The key issue is the degree to which jitter must be controlled through expensive and complex design. No data currently exist, and empirical studies are needed to relate jitter amplitude and frequency to pilot performance.

These research recommendations are considered to be compatible with the image content recommendations of appendixes A through D. Determination of image content for pilot interpretation without adequate attention to display quality parameters will not result in any significant capability improvement. Similarly, improvements in display quality, without regard for image content considerations will yield little gain. A compatible, integrated research effort that takes into account the perceptual content requirements of the trainee as well as the image quality variables is therefore seen as most promising.

REFERENCES

Chase, W. D.
1970 Evaluation of several TV display system configurations for visual simulation of the landing approach. IEEE Transactions on Man-Machine Systems 11:140-149.

Farley, W. W., and Gutmann, J. C.
1980 Digital Image Processing Systems and an Approach to the Display of Colors of Specified Chrominance. Technical Report HFL-80-2. Blacksburg, Va.: Virginia Polytechnic Institute and State University.

Fowler, F. D., and Jones, D. B.
1972 Target Acquisition Studies: (1) Transition from Direct to TV Mediated Viewing, and (2) Target Acquisition Performance with Color vs. Monochrome TV Displays. Orlando, Fla.: Martin Aerospace.

Gogel, W. C., and Tietz, J. D.
1973 Absolute motion parallax and the specific distance tendency. Perception and Psychophysics 13:284-292.

Gutmann, J. C., Snyder, H. L., Farley, W. W., and Evans, J. E.
1979 An Experimental Determination of the Effect of Image Quality on Eye Movements and Search for Static and Dynamic Targets. Technical Report AMRL-TR-79-51. Wright-Patterson AFB, Ohio: Air Force Aerospace Medical Research Laboratory.

Humes, J. M., and Bauerschmidt, D. K.
1968 Low Light Level TV Viewfinder Simulation. Phase B: The Effects of Television System Characteristics Upon Operator Target Recognition Performance. Technical Report AFAL-TR-68-271. Wright-Patterson AFB, Ohio: Air Force Avionics Laboratory.

Kraft, C. L., Anderson, C. D., and Elworth, C. L.
1980 Psychophysical Criteria for Visual Simulation Systems. Technical Report AFHRL-TR-79-30. Williams AFB, Ariz.: Air Force Human Resources Laboratory.

Kraft, C. L., and Anderson, C. D.
1980 Psychophysical Criteria for Visual Simulation Systems: Phase II--Experimental Investigations of Display Joints and Scene Inserts. Technical Report AFHRL-TR-80-18. Williams AFB, Ariz.: Air Force Human Resources Laboratory.

Leibowitz, H. W., Shina, K., and Hennessy, R. T.
1972 Oculomotor adjustments and size constancy. Perception and Psychophysics 12:497-500.

Middleton, W. E. K.
1952 *Vision Through the Atmosphere*. Toronto: University of Toronto Press.

Roscoe, S. N.
1951 *Flight by Periscope*. Aeronautics Bulletin No. 9. University of Illinois. Chicago.

Semple, C. A., Hennessy, R. T., Sanders, M. S., Cross, B. K., Beith, B. H., and McCauley, M. E.
1980 *Aircrew Training Device Fidelity Features*. AFHRL-TR-80-36. Wright-Patterson Air Force Base, Ohio. Advanced Systems Division, Air Force Human Resources Laboratory. AD-A094 665.

Snyder, H. L.
1973 Image quality and observer performance. In L. M. Biberman, ed., *Perception of Displayed Information*. New York: Plenum Press.

Snyder, H. L.
1974 Face recognition on a television display. *Human Factors* 16:300-307.

Snyder, H. L.
1980 *Human Visual Performance and Flat Panel Display Image Quality*. USN Technical Report ONR-80-1. Blacksburg, Va.: Virginia Polytechnic Institute and State University.

Snyder, H. L., Almagor, M., and Shedivy, D. I.
1979 *Raster-Scan Display Photometric Noise Measurement*. Technical Report AMRL-TR-79-13. Wright-Patterson AFB, Ohio: Air Force Aerospace Medical Research Laboratory.

Snyder, H. L., Greening, C. P., and Calhoun, R. L.
1964 *An Experimental Comparison of TV and Direct Vision for Low Altitude Target Recognition*. Technical Report T-46/3111-4. Anaheim, Calif.: Autonetics.

Snyder, H. L., Keesee, R. L., Beamon, W. S., and Aschenbach, J. R.
1974 *Visual Search and Image Quality*. Technical Report AMRL-TR-73-114. Wright-Patterson AFB, Ohio: Air Force Aerospace Medical Research Laboratory.

Snyder, H. L., and Maddox, M. E.
1978 *Information Transfer from Computer-Generated, Dot-Matrix Displays*. Technical Report HFL-78-3/ARO-78-1. Blacksburg, Va.: Virginia Polytechnic Institute and State University.

Snyder, H. L., Wyman, M. J., and Sturm, R. D.
1966 *Functional Performance Requirements for a Fixed-Base Air-to-Ground Simulator*. Technical Report C6-782/2111. Anaheim, Calif.: Autonetics.

Woodruff, R. R.
1979 Effects of Varying Visual Display Characteristics of the T-4G Flight Simulator. Technical Report AFHRL-TR-79-17. Williams AFB, Ariz.: Air Force Human Resources Laboratory. AD-A071 410.

APPENDIX F

FLIGHT SIMULATOR WORKSHOP
COMMITTEE ON VISION
NATIONAL RESEARCH COUNCIL

Agenda	19 June 1980		
8:30 - Welcome	OT Orientation and Briefing		M. Rockway
9:00 - 11:00	OT Vision Research Overview:		
	9:00-9:20	T-4G Collimation and Color Studies	R. Woodruff
	9:20-9:40	Visual Texture and Other Clues	G. Buckland
	9:40-10:00	Vertical Object Cues	R. Engel
	10:00-10:20	Visual/Vestibular & Color Studies	R. Kellogg
	10:20-11:00	The Use of Perceptual Data in Flight Simulation Design	K. Boff
11:00 - 12:00	ASPT Orientation Tour		
12:00 - 13:00	Lunch, Officers' Club		
13:00 - 13:30	Hardware Developments		B. Erikson
13:30 - 14:00	Future Directions		G. Buckland
14:00 - 17:00	Committee on Vision:		
	14:00-14:15	Introduction	W. Richards
	14:15-15:00	Visual Psychophysics: Size-Change and Disparity-Change Channels	D. M. Regan
	15:00-15:45	Recovering Surface Orientation: A Computational View	K. Stevens
	16:00-17:00	General Discussion	

20 June 1980

9:00 - 9:30	Formulation of Problem: Limitations to Low-Level Flight	W. Richards
9:30 - 11:00	Discussion of Important Visual Factors for Simulating Low-Level Flight	
11:00 - 11:30	Listing and Rating of Effectiveness of Visual Cues	
11:30 - 12:00	KYST Analysis	D. Fender
12:00 - 13:00	Lunch	
13:00 - 14:00	Attentional Factors	W. Schneider
14:00 - 14:30	Response Measures and Scan Strategies	Y. Zeevi
14:30 - 15:00	Helicopter Flight Simulation	R. Wright
15:00 - 16:00	General Discussion	
16:00 -	Adjournment	

Participants

K. Boff
G. Buckland
S. Collyer
J. Christiansen
K. Dismukes
D. Fender
F. Gomer
R. Haber
P. Iampietro
T. Longridge
E. Martin
R. Kellogg
D. Regan
W. Richards
W. Schneider
H. Snyder
K. Stevens
H. Wilson
R. Woodruff
R. Wright
L. Young
Y. Zeevi

STEERING GROUP ON FLIGHT SIMULATION

Whitman Richards (Chair), Department of Psychology, Massachusetts Institute of Technology
Derek Fender, Jorgensen Laboratory of Information Science, California Institute of Technology
Ralph Haber, Department of Psychology, University of Illinois
Julian Hochberg, Department of Psychology, Columbia University
Herschel Leibowitz, Department of Psychology, Pennsylvania State University
David Regan, Department of Physiology and Biophysics, Dalhousie University, Halifax, Nova Scotia
Harry Snyder, Department of Industrial Engineering and Operations Research, Virginia Polytechnic Institute and State University

Staff

Key Dismukes, Study Director
Kent Stevens, Consultant
Llyn Ellison, Administrative Secretary

COMMITTEE ON VISION

Derek H. Fender (Chair), Jorgensen Laboratory of Information Science, California Institute of Technology
Anthony Adams, School of Optometry, University of California, Berkeley
Eliot L. Berson, Harvard Medical School
John E. Dowling, Department of Biology, Harvard University
Julian Hochberg, Department of Psychology, Columbia University
Dorothea Jameson, Department of Psychology, University of Pennsylvania
Ken Nakayama, Smith-Kettlewell Institute of Visual Sciences, San Francisco
Luis M. Proenza, Department of Zoology, University of Georgia
Robert Sekuler, Departments of Psychology, Ophthalmology, Neurobiology/Physiology, Northwestern University
Harry Snyder, Department of Industrial Engineering and Operations Research, Virginia Polytechnic Institute and State University

Staff

Key Dismukes, Study Director
Barbara Brown, Research Assistant
Llyn Ellison, Administrative Secretary